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[redacted] ALTITUDE PERFORMANCE EVALUATION OF THE MAIN RETROGRADE THRUST ROCKET FOR THE SURVEYOR LUNAR SPACECRAFT (SUMMARY OF NINE TE-364 FIRINGS)

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ARO, Inc.

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ROCKET TEST FACILITY
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~~GROUP 4~~
~~Downgraded at 3 year intervals; declassified after 12 years~~

A. F. Domal
ARO, Inc.

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FOREWORD

(U) The test program reported herein was sponsored by the National Aeronautics and Space Administration (NASA) with technical liaison provided by the Jet Propulsion Laboratory (JPL). This test program was requested by the Hughes Aircraft Company to support the Surveyor Program under System 921E. The spacecraft's main retrograde thrust motor (TE-364) tested in this program was manufactured by the Thiokol Chemical Corporation, Elkton, Maryland.

(U) Testing was conducted by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), in Propulsion Engine Test Cell (J-5) of the Rocket Test Facility (RTF), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The results reported herein were obtained during the periods from July through September 1964, and May 13 through 20, 1965, under ARO Project Numbers RP1528 and RP1429, and this manuscript was submitted for publication on October 28, 1965.

(U) This report is classified to prevent unauthorized access to performance data of the Thiokol TE-364 solid-propellant rocket motor and its propellant formulation.

(U) This report contains classified information extracted from "Documentation Brochure -- Engines A22-2, A22-3, and A22-4, Surveyor Main Retro Engine Tests at AEDC, Tullahoma, Tenn (U) -- E31-65, April 5, 1965," and also from "Documentation Brochures for Engines A21-17, A21-18, A21-23, and A21-24 Surveyor Main Retro Engine Tests." E59-64, May 1964, Confidential, Group 4.

(U) The Surveyor program in Propulsion Engine Test Cell (J-5) required the development of a horizontal multicomponent thrust stand and use of a supplied motor/propellant thermal gradient conditioning system.

(U) This technical report has been reviewed and is approved.

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CONFIDENTIAL ABSTRACT

[redacted]) Nine Thiokol Chemical Corporation TE-364, spherical, solid-propellant rocket motors, designed for use as the main retrograde thrust motor in the Hughes Aircraft Company Surveyor Spacecraft, were tested in Propulsion Engine Test Cell (J-5) at maximum simulated altitudes ranging from 110, 000 to 116, 000 ft. The objectives of testing were to: demonstrate an altitude ignition capability, measure altitude ballistic performance at a preselected grain temperature and also with a thermal gradient imposed on the motor/propellant assembly, determine the axial thrust vector excursion throughout motor operation, verify structural integrity of each motor during operation at near vacuum conditons, measure the low-range combustion chamber pressure after primary burning is complete, accomplish and document the AMR antenna separation, record dynamic forces at motor mounting plane, and measure exhaust plume radiation heat flux. The nine motors were ignited successfully at simulated altitudes varying from 75, 000 to 100, 000 ft. The average simulated altitude during motor burning ranged from 92, 000 to 112, 000 ft. The specific impulse for the nine motors ranged from 289. 0 to 291. 4 lb_f-sec/lb_m.

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SECTION I
INTRODUCTION

[redacted]) The Surveyor project is part of NASA's unmanned lunar exploration program. The Surveyor spacecraft is composed of several electronic and mechanical assemblies mounted on a spaceframe designed to make a "soft" landing on the lunar surface and gather scientific data (Fig. 1). This information will affect the design requirements of future manned and unmanned lunar spacecraft. Advanced versions of this spacecraft are planned to perform light logistic missions in direct support of the Apollo program.

[redacted]) On a typical mission the spacecraft will be launched by an Atlas/ Centaur vehicle, and approximately 66 hr (and several maneuvers) later the Surveyor will approach the moon and align its velocity vector to the main retrograde thrust rocket motor. At a preselected altitude, the altitude marking radar (AMR) generates a signal resulting in the ignition of the spacecraft liquid vernier engines and the TE-364 solid-propellant main retrograde thrust motor. When the main retrograde thrust rocket burns out, it is ejected from the spacecraft; at this point the relative velocity of the spacecraft is low. From this point on, the flight control electronics, using a doppler velocity sensor system, further control descent with the three vernier engines. When the vernier engines stop, the spacecraft descends to the lunar surface, cushioned by the landing gear.

[redacted]) The Surveyor Main Retrograde Thrust Motor (Fig. 2) was tested in Propulsion Engine Test Cell (J-5) in a series of motors tested in two projects (Refs. 1 through 9). The motors were loaded with various propellant weights ranging from 1200 to 1300 lb. All motors were equipped with a flightweight, 53:1 area ratio, exhaust nozzle.

[redacted]) This report presents a summary of the results of testing nine TE-364 solid-propellant rocket motors with selected comparisons and conclusions. Objectives of testing these rocket motors at simulated altitude were to: demonstrate an altitude ignition capability, measure altitude ballistic performance at a preselected grain temperature and also with a thermal gradient imposed on the motor/propellant assembly, determine the axial thrust vector excursion throughout motor operation, verify structural integrity of each motor during operation at near vacuum conditions, measure the low-range combustion chamber pressure after primary burning is complete, accomplish and document the AMR antenna separation, record dynamic forces at motor mounting plane, and measure exhaust plume radiation heat flux. These tests were accomplished under two basic projects: one for the thrust vector excursion program (motors S/N A21-11, -12, -17, -18, -23, -24) and one for the thermal gradient program (motors S/N A22-2, -3, -4).

SECTION II
APPARATUS

2.1 TEST ARTICLE

[redacted] The Thiokol TE-364 is a full-scale, flightweight, solid-propellant rocket motor designed for use as the main retrograde thrust system on the Surveyor spacecraft. The spherical combustion chamber (Fig. 3) is 36.8 in. in diameter, 0.04 in. thick, and is constructed of Ladish D6AC steel with an ultimate strength of 220,000 psi. The motor combustion chamber is lined with TP-H-301 Polymer and loaded into an internal star configuration (Fig. 4) with TP-H-3062, a composite solid propellant (ICC Class B) with the following composition: Polymer (binder), MAPO (curing agent), ERL500 (curing agent), aluminum (fuel), and ammonium perchlorate (composite fuel).

[redacted] The motor is equipped with a nominal 53:1 expansion ratio (A/A*) (slightly contoured) nozzle (Fig. 5), whose structure is composed of a fiber glass outer layer and carbon cloth phenolic inner layer with an inner liner of bulk carbon phenolic.

[redacted] The nozzle is equipped with a Graph-i-tite Grade GX (density 1.90 gm/cc) throat insert and a 7075-T6 aluminum attachment flange. The nozzle, which is partially submerged, has an exit ID of 24 in. The motor has three mounting lugs, which are attached at the equator and at the motor aft closure flange. The motor cases were externally coated either with a zinc chromate paint or with a plastic compound. The nozzle closure (dust seal) was removed before each motor was fired; however on S/N A21-17 and A21-18, an AMR antenna dish was attached to the nozzle exit stiffening ring. The total loaded weight of the motors ranged from 1370.7 to 1438.63 lb. The propellant weight ranged from 1197.80 to 1299.43 lb.

[redacted]) Each motor was ignited by a propellant-type igniter (called a Pyrogen® by Thiokol) (Figs. 2 and 3), which was loaded with approximately 0.5 lb of TP-H-3062 solid propellant. The ignition within the Pyrogen was initiated by a squib-initiator, which contained 19 gm of $BKNO_3$ pellents and two Hi-shear PC37 electric squibs. The motor ignition was activated by application of a 5-amp current (28 v dc) to each of the two electric squibs.

[redacted] Each squib-initiator and Pyrogen was installed and pressure checked by the motor manufacturer before arrival at AEDC. Inadvertent or premature ignition of each motor by the protechnic squibs was prevented by a safe/arm (S/A) mechanism (integrally mounted), which physically interrupted the firing train from the squibs to the $BKNO_3$ pellets. As long as the S/A was locked in the "S" position, the motor was stored and handled as an ICC Class B explosive. Some of the S/A mechanisms were manually operated, but the final configuration (Fig. 6) (flightweight S/A's) was electrically activated.

2.2 TEST CELL AND INSTALLATION

[redacted] The motor was fired in Propulsion Engine Test Cell (J-5) (Ref. 10 and Fig. 7), a horizontal test cell designed for testing of solid-propellant rocket engines up to 100,000 lb thrust and at altitudes in excess of 100,000 ft. The cell is a cylindrical section 16 ft in diameter and 50 ft long.

[redacted]) Axial thrust was reacted by a thrust abutment mounted on two 33-in. "I" beams which are anchored to the cell foundation (approximately 600,000 lb of reinforced concrete). The pitch and roll forces are reacted directly to the same two beams, whereas the yaw forces are reacted by two columns (Fig. 7b) which extend through bellows seals in the east wall of the test cell and are anchored in a vertical "seismic mass" (Fig. 7c) consisting of approximately 600,000 lb of reinforced concrete.

[redacted]) The test cell is equipped with a temperature conditioning system designed to maintain the test cell and motor at any prescribed temperature of 60 to 100 ± 5°F from motor installation until pre-fire pumpdown. This system was modified using liquid-nitrogen cooling to maintain 50 ± 5°F for the thrust vector excursion measurements. The thermal gradient program used special temperature conditioning equipment.

[redacted]) The rocket motor discharged into a 53-in.-diam water-cooled, diffuser duct section. The exhaust-gas mixture flowed from the test cell diffuser ducts through a spray bank cooler. These spray banks as well as all other test cell support functions were activated well in advance of the motor firing time in order to achieve stable flow and thereby minimize vibration to the thrust cradle force measuring elements.

2.3 THERMAL GRADIENT CONDITIONING EQUIPMENT

[redacted] Temperature conditioning equipment, furnished and operated by the Thiokol Chemical Corporation (TCC), was used to impose thermal gradients across motors S/N A22-2, A22-3, and A22-4. This equipment consisted of temperature conditioners, buffer boxes, gradient conditioning bag (in two sections), three skirt thermoconditioning pads, circulating ducts, and a complete motor temperature conditioning/recording complex (shown in Fig. 8). The system was set up using the Wyle units as basic conditioners with buffer boxes in series to increase the temperature conditioning capability. The added cooling provided by the buffer boxes was accomplished by the periodic injection of gaseous CO_2 flashed (using an orifice) from a liquid. The conditioning gas flowed through the forward and aft sections (Zones 1 and 2, respectively) of the gradient conditioning bag and then back to the conditioning units. The remaining part of the gradient conditioning system (Zone 3) was the skirt thermoconditioning pads mounted on the three thrust skirts. The skirts were cooled by flashing liquid CO_2 and circulating the cooled gas through the pads. A complete cycle of all three conditioning zones is shown schematically in Fig. 8.

2.4 FORCE MEASURING HARDWARE

[redacted] The Surveyor force measuring system (thrust cradle) was designed, fabricated, and assembled to fulfill a "stiff" stand concept for measuring more than one component of a force with extremely low interaction. In addition to the massive reaction masses for the thrust measurement columns, the load cells and compatible flexures were highly oversized. The axial load cell and flexures used were rated 0- to 100,000-lb load cell, whereas the yaw and pitch load cells used had a rated full range of 0 to 6000 lb. The roll load cell used had a 0- to 100-lb rated range. These load cells were carefully calibrated in the ranges used and represent one of the necessary elements in the "stiff" stand concept. This system was used for the six-component thrust vector excursion measurements. A complete analysis and discussion of this system is presented in Refs. 3 through 9.

[redacted]) Each motor was installed into, and restrained by, a thrust cradle (Fig. 9), which was supported by two vertical (pitch) load cell columns and restrained in the horizontal plane by yaw and axial load cell columns. An additional aft vertical load cell column was used to restrain the cradle in roll. All load cell columns were flexure mounted (Fig. 9). The axial leg of the six-component thrust system was equipped with a remotely operated, in-place, binary, deadweight, axial load cell calibrator. The yaw (horizontal) load cells were equipped with an in-place physical calibrator which could be operated at sea-level condition. The pitch load cells were calibrated with a separate pitch calibrator, which was attached at the motor mounting plane and allowed the pitch load to be applied at sea-level conditions. The roll load cell was calibrated with a deadweight calibrator, which could be loaded at sea-level conditions. The force measuring system was physically calibrated in place, for axial forces up to 10,000 lb_f, yaw forces up to 100 lb_f, pitch forces up to 1200 lb_f, and roll moment up to 250 in.-lb.

[redacted] This same thrust stand system concept was used for the thermal gradient tests; however, the yaw, pitch, and roll load cells were removed. The thrust stand used in these tests was capable of measuring axial forces in excess of 10,000 lb_f and was calibrated in the same manner as described in the foregoing paragraphs.

[redacted]) An important and necessary element in the force system was a highly precise alignment capability (Fig. 10). The thrust cradle was built with close tolerances and was laboratory inspected to ensure critical dimensions. Dowel pins were used to accurately locate the hardware physical elements. The cradle was optically aligned in the test cell using optical targets attached to the thrust cradle by laboratory personnel.

[redacted]) The thrust cradle was equipped with "twang" or step input dynamic calibrators in the yaw plane and in roll about the thrust axis. When a simulated motor was used, the motor/cradle thrust system exhibited natural frequencies of 32 cps in yaw translation and 24.5 cps in rotation in the yaw plane. This system also exhibited a natural frequency of 41 cps in the axial direction and approximately 17 cps in roll about the axial centerline. The indicated natural frequency in the pitch plane is approximately 25 to 30 cps.

2.5 INSTRUMENTATION

[redacted]) Instrumentation was provided to measure axial thrust, yaw force, pitch force, roll force, motor ignition and combustion chamber pressure, low-range combustion chamber pressure, motor skin temperature, propellant grain temperature, motor case strain, and test cell ambient pressure and temperature (Fig. 11).

[redacted]) Axial thrust was measured with the six-component thrust stand using a 100,000-lb, multiple-output, strain-gage-type axial load cell. Yaw forces and pitch forces were measured with 6000-lb, multiple-output, strain-gage-type load cells. The roll force was measured with a dual-output, bonded, strain-gage-type load cell, rated for 0 to 100 lb.

Universal flexures isolated all load cells from any forces other than those induced through the load cell axes. The axial load cell instrumentation channels were spanned for 0 to 10,000 lb. The yaw load cell channels were spanned for 0 to ±100 lb, the pitch load cell channels were spanned for 0 to ±1500 lb, and the roll load cell channels were spanned for 0 to ±50 lb using the laboratory calibrations as a basis.

[redacted]) Pressures were measured by strain-gage-type pressure transducers, and temperatures were measured by iron-constantan and Chromel®-Alumel® thermocouples. The pressure transducer channels were spanned using the laboratory calibrations. The thermocouples were connected to a 150°F reference junction, and their channels spanned with a National Bureau of Standards temperature table as basis (Ref. 11).

[redacted]) Load cell, pressure transducer, and thermocouple outputs were recorded on the digital data acquisition systems with a nominal error from input to output tape of ±0.1 percent full range.

[redacted] The output signal from each measuring device of the primary data was recorded by independent instrumentation systems or channels. The primary digital data consisted of two axial thrust channels, four yaw force channels, two pitch force channels, one combustion chamber pressure channel, one roll force channel, and one test cell pressure channel. This digital data system recorded in the following manner: Each output signal was indicated in totalized digital form on a visual readout of a millivolt-to-frequency converter-totalizer (Vidar®), and also was recorded in analog form on a photographically recording, galvanometer-type oscillograph. A magnetic tape system recording in frequency form, stored the digital signals from the converter-totalizer for reduction at a later time by an electronic digital computer. This digital computer-complex provided a printed tabulation of absolute values and total integrals at time intervals of 0.1 sec.

[redacted]) This primary digital data system is equipped with an adjustable full-scale resolution for various input voltages. This feature is uniquely compatible with the "stiff" stand concept in that the reduced voltage outputs associated with using grossly oversized load cells to measure small forces can be associated with a full-scale digital resolution. Thus the value of a special calibration over a small portion of a load cell's rated range is not lost.

[redacted] A second digital system, called a multi-input, analog-to-digital converter (Microsadic®) was used to record selected channels of axial thrust, yaw force, pitch force, roll force, test cell ambient pressure, all temperature channels, and low-range combustion chamber pressures on a magnetic tape system, which stored the time shared channels for reduction at a later time by a digital computer.

[redacted]) A separate 1-in. tape recorder system was used to record the vibration signals from three crystal load cells (Fig. 12) and various accelerometers. These systems were set up and calibrated by RTF and Hughes personnel. The magnetic tape was copied and transmitted to Hughes Aircraft Company for power density and spectral analysis.

[redacted] The oscillograph, recording with a paper speed of 40 in. /sec, provided an independent backup of all operating instrumentation channels except the temperatures. Selected channels of axial thrust, motor combustion chamber pressure, low-range combustion chamber pressure, test cell ambient and temperature pressure, and motor skin temperatures were also recorded on null-balance, potentiometer-type strip charts for immediate analysis following the test firing.

[redacted] Visual observation of the motor firing was provided by a closed-circuit television monitor. High-speed, motion-picture cameras were used to provide a permanent visual record on the AMR antenna separation and the test firings.

2.6 INSTRUMENTATION CALIBRATION

[redacted] The thrust calibrator weights, thrust load cells, and pressure transducers were physically calibrated with NBS secondary standards in a laboratory before installation in the test cell. After installation of the various transducers in the test cell, the complete instrumentation systems were calibrated at sea-level and pressure altitude conditions.

[redacted]) The axial thrust instrumentation systems were calibrated physically with a binary deadweight calibrator using secondary standard weights (accurate to within 0.01 percent), in conjunction with a bellcrank mechanism having an accurately measured lever arm. The calibrator is hydraulically operated and remotely energized from the control room, thus allowing calibration at altitude pressure conditions immediately prior to firing. The yaw force systems were calibrated in place at sea-level conditions using a force applied through a standard load cell and with a laboratory devised electrical step calibration at pressure altitude conditions. The pitch load cells were calibrated with a calibrator device which was mounted at the motor mounting lugs and simulated an empty motor. Deadweights were attached to the calibrator at each of two locations to simulate motor propellant weight change during burning. The two deadweight loading points were located at the approximately motor pre- and post-fire CG locations. The roll load cell was calibrated by applying deadweight loads at a known point on the thrust cradle.

[redacted]) The pressure systems were calibrated by a laboratory devised electrical step calibration, which placed known resistances into the transducer circuit to simulate a known input signal level. The resistors for all electrical calibrations were selected from the control room. This procedure allowed calibration of the instrumentation systems at altitude pressure conditions immediately prior to firing.

SECTION III
PROCEDURE

[redacted]) Upon arrival at AEDC, each motor was stored in a temperature controlled environment (bunker) of 70 ± 5°F. The motor was within its shipping container, and the S/A was "safe."

[redacted]) A physical and radiographic inspection was made to determine if any damage had been caused in transit and to ensure that each motor was acceptable for firing at RTF (Fig. 13).

[redacted]) A special mounting ring was fitted to each motor mounting lug hole pattern. This same mounting ring was also fitted and pre-aligned to the thrust cradle; during this operation each ring for the thrust vector excursion program was match drilled to the cradle, and roll pins (dowels) were inserted to allow the ring to be removed and handfitted to the motor. Then it was returned with motor attached to the same pre-aligned position within the cradle (Fig. 13). These operations were performed with motor and cradle in the vertical position. The motor cradle was then turned to the horizontal position, and the alignment measurements were made of the misalignment of the nozzle centerline with respect to the system (cradle) centerline. Alignment methods included placing the motor cradle on a granite surface table and placing optical targets into the nozzle throat and exit planes (Fig. 14). An optical transit/square was used for the alignment measurements. The cradle was manufactured to close tolerances and inspected under laboratory conditions so that all critical dimensions were accurately known, and since the cradle was equipped with optical targets, it was possible to read the cradle or nozzle alignment to within 0.005 in. After the motor/cradle misalignment was recorded at the preparation area, the assembly was transported to the test cell and installed. Then the cell temperature conditioning was begun, and the motor/cradle was conditioned at 50 ± 3°F for 60 hr for the thrust vector excursion program.

However, for the thermal gradient program, each motor was pre-conditioned in a refrigerated trailer at 50 ± 5°F for 45 hr.

([redacted]) After temperature conditioning was completed for the thrust vector excursion program, the thrust cradle optical targets were used to make a final alignment adjustment of the motor/cradle to the cell thrust-takeout hardware. The yaw and pitch force arms were separately checked to ensure that they were parallel to each other and perpendicular to the axial centerline of the thrust cradle. The cell temperature conditioning system held the cell ambient temperature at the preselected level during the pre-firing installation, alignment, and calibration procedures. When the sea-level calibrations were completed, the test cell pressure was reduced to desired pressure altitude conditions using the plant rotating exhauster equipment. Then the altitude pre-firing calibrations were performed at a test cell pressure of 0.5 psia. The desire for an extremely stable background for the instrumentation transducers is in keeping with the "stiff" stand concept and precluded the use of the auxiliary pumping system (which was capable of maintaining 0.1 psia) for either the altitude calibration or the firing.

([redacted]) After temperature conditioning was completed for the thermal gradient program, each motor (in turn) was moved back to the rocket preparation area, loaded into the cradle (Fig. 8b), and then transported to the test cell and installed. With the use of optical targets attached to the cradle and optical alignment equipment, the motor/cradle was aligned to the thrust-takeout hardware to within ±1/64 in. During motor/cradle installation and alignment, the Thiokol Chemical Corporation (TCC) gradient conditioning equipment (Fig. 8c) was connected and used to recondition each motor (at the pre-gradient conditioning temperature) for twice the time out of the required pre-gradient temperature limits. Upon completion of all pre-gradient conditioning requirements, the TCC equipment was set to hold the motor zone temperatures at the pre-selected levels shown in Table I. The motors were gradient conditioned for approximately 18 hr. During this time, sea-level calibrations were performed, and all instrumentation and recording equipment underwent final checks and adjustments. After the completion of gradient conditioning requirements, the test cell was sealed and reduced to pressure altitude conditions using the plant rotating exhauster equipment. Then the altitude pre-firing calibrations were performed at a nominal test cell pressure of 0.5 psia.

([redacted]) After the altitude calibrations were performed and the interactions and force calibrations manually reduced, studied, and found to be satisfactory, the firing circuit resistance and voltage were adjusted to give the desired firing current of 5 amp/squib.

[redacted] A countdown procedure was begun which operated the cell support functions, activated the entire data recording-measuring complex, and fired the motor.

[redacted]) After motor burnout, the data complex (Micro-SADIC) was used to record post-firing case and nozzle temperatures out to T + 10 min, and then the post-firing altitude calibrations were performed and recorded.

[redacted] Then the test cell pressure was returned to sea-level ambient conditions. When the cell temperature conditioning system had returned to the pre-firing level, post-firing alignment measurements of the cradle were recorded.

[redacted] The expended motor with cradle was returned to the inspection area. The motor was weighed, inspected, photographed, removed from the cradle, and replaced in the shipping container. Post-firing inspection consisted of measuring the nozzle throat and exit dimensions and photographing any unusual features (anomalies) incurred during firing.

SECTION IV
RESULTS AND DISCUSSION

[redacted]) Nine Thiokol TE-364 solid-propellant rocket motors were successfully ignited and operated at simulated altitude (near vacuum) in Propulsion Engine Test Cell (J-5). The motors were tested in two projects:

I. Thrust Vector Excursion Measurement

   a. Motor S/N A21-11 (three-component stand)

   b. Motor S/N A21-12 (three-component stand)

   c. Motor S/N A21-17 (six-component stand)

   d. Motor S/N A21-18 (six-component stand)

   e. Motor S/N A21-23 (six-component stand)

   f. Motor S/N A21-24 (six-component stand)

II. Thermal Gradient Program

   a. Motor S/N A22-2 (single component stand)
   b. Motor S/N A22-3 (single component stand)
   c. Motor S/N A22-4 (single component stand)

These programs are defined in Refs. 1 through 9.

[redacted] The primary objectives of testing were to: (1) demonstrate altitude ignition capability, (2) measure altitude ballistic performance of motors with preselected grain temperature conditioning configurations imposed on the motor/propellant assembly, (3) determine the axial thrust vector excursion throughout motor operation, (4) verify structural integrity of the motor during operation at near vacuum conditions, and (5) measure the low-range combustion chamber pressure after primary burning was completed. Secondary objectives consisted of measuring motor skin temperature, recording motor vibration signals, documenting antenna separation, and measuring exhaust plume heat flux.

[redacted] The data to fulfill these objectives for the nine firings are presented in Refs. 1 through 8; however, this summary report presents a comparison of basic primary data for all motors tested.

4.1 ALTITUDE IGNITION CHARACTERISTICS

[redacted] The nine motors were ignited successfully at simulated altitudes ranging from 75, 000 to 108, 000 ft (geometric altitude, Z, Ref. 12). The following table allows quick comparisons of the nine firings.

Motor S/N	Motor Ignition Temperature, °F	Ignition Altitude, ft	Squibs	Thrust Delay, msec
A21-11	48	77, 000	2	125
A21-12	49	76, 500	2	127
A21-17	52	75, 000	2	126
A21-18	53	78, 000	2	134
A21-23	54	76, 000	1	122
A21-24	53	78, 000	1	119
A22-2	Gradient (49)*	106, 000	2	125
A22-3	Gradient (45)*	108, 000	2	130
A22-4	Gradient (34)*	107, 000	1	99

*Estimated average grain temperature.

[redacted] The thrust delay time is defined as the time from the ignition pulse to the first perceptible rise in thrust. This time is a small, but important, part of the spacecraft flight control program. From these data, a general conclusion can be made that the nine motors tested have an average thrust delay time of 123 msec, with a standard deviation from a mean value of ±0.09 percent.

4.2 INTERIOR BALLISTIC PERFORMANCE

([redacted]) The total burning time, defined as the time from the ignition pulse until the last indication of combustion chamber pressure or thrust as indicated by the full-range transducers, is presented in the table below.

Motor S/N	Total Burning Time, sec	Propellant Weight, lb	Grain Temperature, °F
A21-11	46.5	1197.80	80
A21-12	46.5	1198.76	49
A21-17	46.5	1228.96	52
A21-18	48.3	1229.55	53
A21-23	46.6	1229.01	54
A21-24	47.0	1231.82	53
A22-2	50.0	1299.43	Gradient (49)*
A22-3	50.0	1250.61	Gradient (45)*
A22-4	52.0	1250.59	Gradient (34)*

*Estimated average grain temperature.

([redacted]) The burning time increased 2 sec (from motor A22-3 to A22-4) as a result of the lower mean propellant temperature. The cause for the 2-sec increase for motor A21-18 is not apparent.

([redacted]) The total impulse, corrected to vacuum, for the nine motors tested, ranged from 348,748 to 375,890 lb_f-sec. The impulse data are presented in Fig. 15. These data agree closely with theoretical calculations for constant specific impulse lines; however, the data indicate that there is a constant bias between the thrust vector excursion program and the thermal gradient program of approximately 0.6 percent.

([redacted]) The specific impulse corrected to vacuum (I_s) for the first six motors (thrust vector excursion program) ranged from 290.7 to 291.4 lb_f-sec/lb_m. The six motors tested produced a specific impulse which was repeatable to within ±0.1 percent and resulted in an average I_s of 291.1 lb_f-sec/lb_m with a standard deviation from a mean value of ±0.07 percent. The I_s for the last three motors (thermal gradient program) ranged from 289.0 to 289.5 lb_f-sec/lb_m, with an average value of 289.3 which was repeatable to within ±0.1 percent. The average specific impulse for the nine motors tested was 290.5 lb_f-sec/lb_m, with a standard deviation from a mean value of ±0.29 percent.

[redacted] The performance comparison of motors S/N A22-3 and A22-4 indicates that no significant effect is produced by the two different thermal gradients imposed on these motors. Performance data plots (thrust, combustion chamber pressure, test cell pressure) presented in Figs. 16 and 17 are for 1200, 1230, 1250, and 1300-lb motors (all weights nominal). The difference in the two 1250-lb motors which were conditioned with different thermal gradients (see Table I) is also presented for comparative study.

[redacted] The average overall thrust coefficient (C_F) is deinfed as

$$C_F = \frac{\int_0^{t_B} F\,dt + A_E \int_0^{t_B} P_A\,dt}{A_T \int_0^{t_B} P_C\,dt}$$

where:

F = axial thrust, lb

A_E = average area of nozzle exit, in.^{2}

A_T = average area of nozzle throat, in.^{2}

P_A = test cell ambient pressure, psia

P_C = motor combustion pressure, psia

t_B = total burning time, sec

[redacted]) The average overall thrust coefficient (C_F) (Refs. 1 through 8) ranged from 1.809 to 1.874 for the four 1230-lb motors, and the thrust coefficient for the two 1200-lb motors falls within this interval. The C_F for the four 1230-lb motors can be given as 1.845 ± 2 percent. If the C_F of 1.809 for A21-18 is ignored, then the C_F is 1.857 ± 1 percent. The calculated/measured overall thrust coefficients were 1.864, 1.856, and 1.859 (for A22-2, A22-3, and A22-4, respectively). This represents an average value of 1.859 ± 0.5 percent.

[redacted]) The average overall C_F (weighted average) for all motors tested is 1.858 ± 1.0 percent. This represents a value approximately 3 percent less than theoretical (Ref. 13)

4.3 MOTOR VIBRATION

[redacted]) The last four motors tested in the thrust vector program (motors S/N A21-17, A21-18, A21-23, and A21-24) were instrumented to sense the motor induced vibrations at the three mounting lugs. The crystal load cells (transient force gages) were the most useful in recording changes of the motor produced forces. These sensors were placed between the motor mounting lugs and the thrust cradle. In this manner, the motor compressed the sensor during thrust. Detailed analysis by Hughes Aircraft Company (HAC) personnel to determine the magnitude and frequencies of motor generated vibrations has been accomplished, and the data are presented in Refs. 14 and 15.

[redacted] Two predominant response frequencies (natural frequencies) were identified; these were 310 cps and 940 cps. Responses at higher frequencies were also evident; however, isolation was occurring beyond 2000 cps. These data are taken from the crystal load cells (Ref. 15).

[redacted] The thrust/time history on magnetic tape was used as a forcing function for a further shaker test of a Surveyor model.

[redacted] Hughes personnel concluded "Apart from the ignition, thrust buildup, and mid-burn force transients, the Surveyor retro-engines are considered to be smooth in operation, particularly from the vibration aspect." (Ref. 15)

4.4 COMBUSTION CHAMBER OUTGASSING

[redacted]) Low-range pressure transducers (with mechanical over-range safety stops) were used to measure motor combustion chamber pressure after primary burning was complete.

[redacted]) The low-range pressure data (Fig. 18) for the thermal gradient tests indicate that the motors continued to produce exhaust gases out to the end of data acquisition (T + 10 min). The chamber pressure data presented are not affected by ambient pressure (to T + 10 min) since the cell was maintained at a sufficiently low pressure (approximately 0.1 psia) to result in the motor nozzle throat remaining choked (supersonic flow). The choking pressure ratio was determined by calculating an ambient to chamber pressure ratio assuming ideal gas, one-dimensional, isentropic expansion, gas relationships with $\gamma = 1.16$, and assuming 70-percent pressure recovery in the nozzle exit cone. This ratio was calculated to be 0.87 and represents the critical ratio at which the nozzle throat can become unchoked (flow subsonically).

[redacted]) To estimate the thrust (in vacuum) produced by these gases, the following equation may be used:

$$F = C_F \, (P_C) \, A_T$$

where:

F = axial thrust, lb

C_F = vacuum thrust coefficient

P_C = motor combustion chamber pressure, psia

A_T = post-firing throat area, in.^{2}

[redacted]) This force must be accounted for in the motor spacecraft separation calculations. An estimate of the impulse produced by outgassing of the motors tested from nominal burnout out to 10 min was in excess of 1900 lb_f-sec in each case.

4.5 THRUST VECTOR EXCURSION

[redacted]) The main thrust vector excursion angle in the thrust plane is the greatest motor-created thrust misalignment that the Surveyor spacecraft will have to correct. This vector angle in the thrust plane (or alternately known as the cone angle) is defined as the angle between the resultant thrust vector and the nozzle centerline projected into the thrust plane. The thrust plane contains the resultant thrust vector and is parallel to the nozzle centerline. The spacecraft will also have to correct for a rolling moment about the axial centerline (nozzle centerline), which will exist as long as the thrust plane and nozzle centerline are not coincident.

[redacted]) The maximum thrust vector excursion angle, in the thrust plane, ranged from 0.07 to 0.17 deg and occurred at random times ranging from 15 to 37.5 sec after ignition for the motors which were fired in a six-component thrust stand (Fig. 19). These motors had a maximum thrust vector excursion angle of 0.11 deg (average value) or a median value of 0.12 ± 0.05 deg. The error in the vector angle measurements is estimated to be within ±0.03 deg or less. The thrust vector excursion angle was within specification limits (Ref. 14).

[redacted]) By using 0.15 deg as the assumed maximum vector angle (Ref. 7) in the pitch plane for motors A21-11 and A21-12 (pitch and roll forces were not measured during these two firings), a calculated value of the maximum thrust vector excursion angle in the thrust plane is 0.175 deg for motor A21-11 and 0.153 deg for motor A21-12. These values are based on a normal distribution of the motors tested in the six-component thrust stand.

[redacted]) The maximum rolling moment about the thrust axis always occurred just before burnout or tailoff and ranged from 70 to 140 in.-lb for the four motors tested in the six-component thrust stand. This results in an average rolling moment of 95 in.-lb or a median value of 105 ± 35 in.-lb. A further study of the rolling moment curves (Fig. 20) reveals that the rolling moment varied from -50 in.-lb (counter clockwise) to +140 in.-lb (clockwise) for the four motors tested. This indicates that the capability for rolling-moment correction must include a change in rotation during burning.

[redacted] The values of rolling moment are acceptable to the spacecraft corrective system (Ref. 14).

[redacted]) The shape of the rolling-moment curve indicates that generally throughout each firing the value of rolling moment begins to increase at a rapid rate in the clockwise direction. The shape of the rolling-moment curve is probably affected by the CG-propellant burning correction and by some unknown fixed bias within the thrust stand system. However, the accuracy of the data acquisition system for rolling moment is estimated to be ±15 in.-lb (Ref. 7).

4.6 TEMPERATURE AND HEAT FLUX DATA

[redacted]) Motor temperatures were measured at various locations on the motor case and nozzle. These data are presented for the thermal gradient motors in Fig. 21. These data were recorded for 10 min (Fig. 21) at a test cell pressure of approximately 0.1 psia.

[redacted]) The highest motor case temperatures recorded during the firing time (total burn time) are listed below in tabular form:

Motor	Location	Thermocouple	Temperature, °F
A22-2	Case	TMS-2	216
A22-2	Nozzle	TMN-1	369
A22-3	Case	TMS-3	217
A22-3	Nozzle	TMN-1	303
A22-4	Case	TMS-3	256
A22-4	Nozzle	TMN-1	396

[redacted]) The highest temperatures recorded for each motor during the 10-min period after ignition were 792°F, 614°F, and 754°F (for A22-2, A22-3, and A22-4, respectively). All these maximums were recorded on the forward motor case thermocouples (TMS-4) at 2.75 min (A22-2), 6 min (A22-3), and 2.92 min (A22-4) after ignition.

[redacted]) Review of film from a special motion-picture camera (variable iris), which was used on the last thrust vector test firing, indicates that heating of the nozzle outside surface began before motor burnout or diffuser breakdown.

[redacted]) Radiometers (Hycal Model R-2202-BX-15) and calorimeters (Hycal Model C-1300) were used to measure exhaust plume heat flux during the thrust vector excursion tests. Radiant heat rates of 5 to 6 Btu/ft^2-sec were measured during motor burning. Spacecraft heating from this heat transfer data is under study by Hughes Aircraft Company (Ref. 14).

4.7 STRUCTURAL INTEGRITY

[redacted] As a general statement, the structural integrity of all nozzles was considered excellent. Although there was nozzle spalling, which occurred to some degree in each motor tested (and probably did reduce motor performance), this did not create a serious thrust vector excursion.

[redacted]) Compared with the nozzles of the other eight motors tested, the nozzle on motor A21-23 was more seriously damaged. It must be pointed out that not only did the nozzle spall more and suffer nozzle exit ring damage, but also the throat area increased (erosion) by nine percent. Although this did not seriously affect the thrust vector excursion angle, it most probably did reduce motor performance. This nozzle should be considered marginal when compared to the structural performance of the other nozzles. Even though the nozzle damage was not considered severe, and the motor performed satisfactorily in its present configuration, it might not have sustained an uprated mission.

[redacted]) An Altitude Marking Radar (AMR) antenna dish was attached to the nozzles of motors A21-17 and A21-18. The antenna cleared the nozzle exit cone plane in 40 msec or less. The antenna separation did not affect motor performance. However, on motor A21-18, it did damage an antenna mounting lug, which was normally embedded in the nozzle exit ring. The nozzle on this motor sustained the simulated altitude firing in excellent condition (Refs. 3 and 4).

SECTION V
SUMMARY OF RESULTS

[redacted] The results of the successful ignition and testing of nine TE-364 solid-propellant rocket motors at simulated altitude are summarized as follows:

([redacted]) 1. The maximum thrust vector excursion angle for the four motors tested with a six-component thrust stand ranged from 0.07 to 0.17 deg and occurred at random times from 15 to 37.5 sec after ignition.

([redacted]) 2. The maximum rolling moment about the thrust axis ranged from 70 to 140 in.-lb and occurred just before motor tailoff for each of the motors tested. A further study indicated that the rolling moment varied from -50 to +140 in.-lb, which implies that the spacecraft capability for correcting rolling moment must include a change in rotation during motor burning.

([redacted]) 3. The total impulse corrected to vacuum ranged from 348,750 to 348,950 lb_f-sec for the two 1200-lb motors; from 357,300 to 358,580 lb_f-sec for the four 1230-lb motors; from 361,470 to 362,000 lb_f-sec for the two 1250-lb motors; and 375,890 lb_f-sec for the one 1300-lb motor.

([redacted]) 4. The specific impulse, corrected to vacuum, for the first six motors ranged from 290.7 to 291.4 lb_f-sec/lb_m. Nozzle contour-throat deterioration is the most plausible cause of the lower performance value (290.7 lb_f-sec/lb_m) associated with motor A21-23. For the last three motors (S/N A22-2, -3, -4) tested, the specific impulse ranged from 289.0 to 289.5 lb_f-sec/lb_m. Statistically calculated data indicate that the average specific impulse for the nine motors tested is 290.5 lb_f-sec/lb_m.

([redacted]) 5. The nine motors were successfully ignited at simulated altitudes ranging from 75,000 to 108,000 ft. The nine motors tested had an average thrust delay time of 123 msec with a standard deviation from a mean value of ±0.09 percent.

([redacted]) 6. The motor structural integrity was excellent; however, spalling of the nozzle interior contour surface occurred on all motors tested. Although this did not create serious thrust vector excursion, it probably did reduce motor performance. The performance of the nozzle for motor S/N A21-23, when compared with the performance of the other nozzles in this test series, should be considered marginal, because although the motor performed satisfactorily in its present configuration, it might not have sustained an uprated mission.

([redacted]) 7. Hughes personnel concluded (from all acceleration data required during these tests) that apart from thrust buildup and mid-burn force transients, the Surveyor retro-engines are considered to be smooth in operation, particularly from the vibration aspect.

[redacted] 8. The low-range pressure data indicate that the thermal gradient motors continued to produce exhaust gases up to T + 10 min after ignition.

[redacted]

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2. Domal, A. F. [redacted] "Simulated High Altitude Testing of a Flightweight TE-364-1 Solid-Propellant Retrograde Rocket Motor for the Surveyor Lunar Spacecraft (Phase I - R&D Testing) Motor S/N A21-12." AEDC-TDR-64-262 (AD 356205), January 1965. [redacted]

3. Domal, A. F. and Davis, R. L. [redacted] "Simulated High Altitude Testing of a Flightweight TE-364-1 Solid-Propellant Retrograde Rocket Motor for the Surveyor Lunar Spacecraft (Phase II - Quality Testing) Motor S/N A21-17." AEDC-TR-65-21 (AD 357407), February 1965. [redacted]

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5. Domal, A. F., Davis, R. L., and Turner, W. A. [redacted] "Simulated High Altitude Testing of a Flightweight TE-364-1 Solid-Propellant Retrograde Rocket Motor for the Surveyor Lunar Spacecraft (Phase II - Quality Testing) Motor S/N A21-23." AEDC-TR-65-41 (AD 358671), March 1965. [redacted]

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7. Domal, A. F. [redacted]) "Altitude Performance Evaluation of the Main Retrograde Thrust Rocket for the Surveyor Lunar Spacecraft Thrust Vector Excursion Analysis (Summary of Six TE-364-1 Firings)." AEDC-TR-65-77 (AD360118), May 1965. [redacted]

8. Turner, W. A. and Domal, A. F. [redacted] "Simulated High Altitude Testing of Three Flightweight TE-364-5 Solid Propellant Rocket Motors for the Surveyor Lunar Spacecraft (Thermal Gradient Testing) Motors S/N A22-2, A22-3, A22-4." AEDC-TR-65-176 (AD365262), September 1965. [redacted]

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11. National Bureau of Standards, Circular No. 561 (Equivalent MIL-W-5846-A).

12. Minzner, R. A., Champion, K. S. W., and Pond, H. L. "The ARDC Model Atmosphere." AFCRC-TR-59-267, August 1959.

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14. Spicer, L. M. [redacted] "Quality Assurance Testing of the Surveyor Main Retro Engine at AEDC." Engineering Record Number 163, December 1964. [redacted] (Published by Hughes Aircraft Company)

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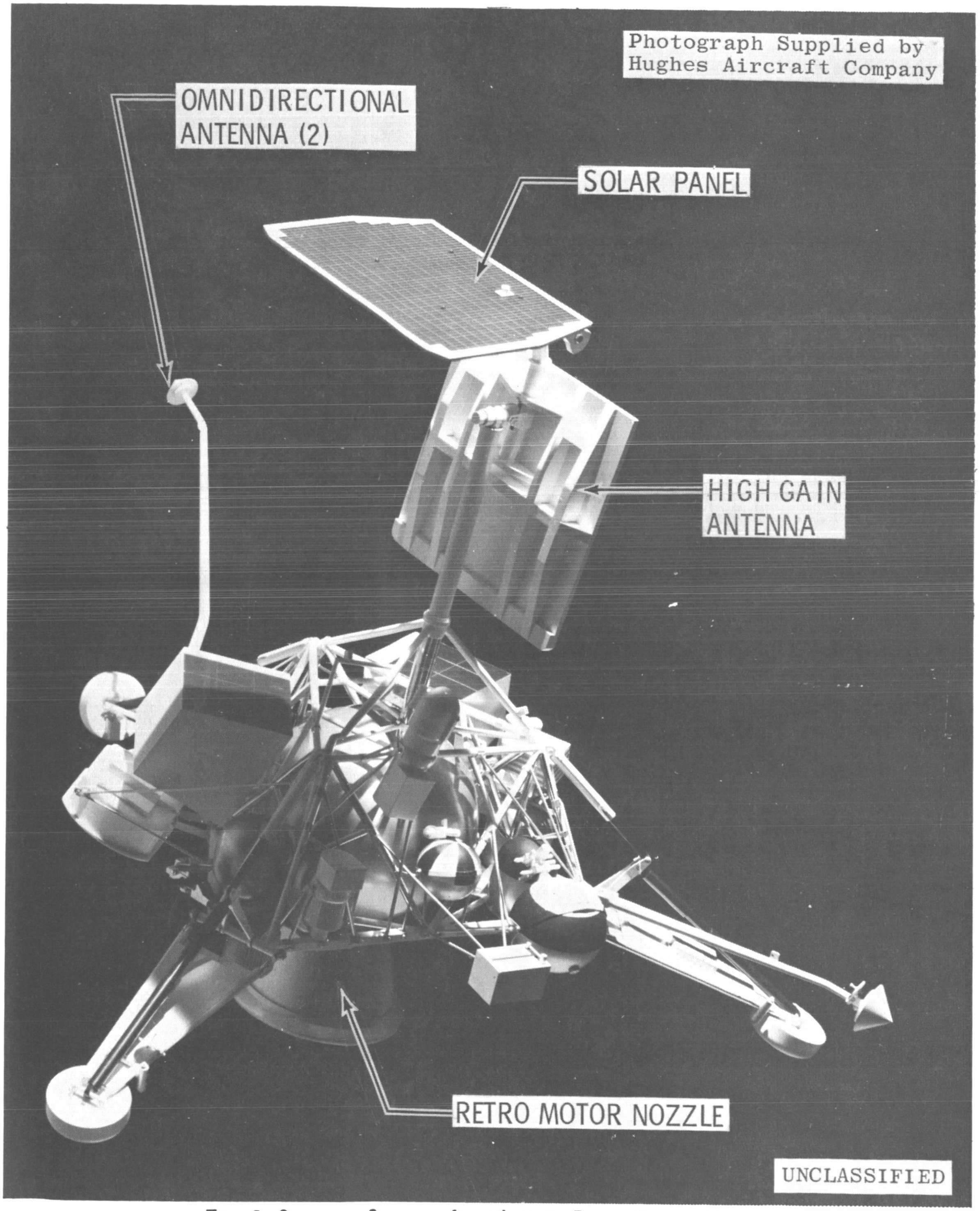


Fig. 1 Surveyor Spacecraft with Main Retro-Rocket Motor

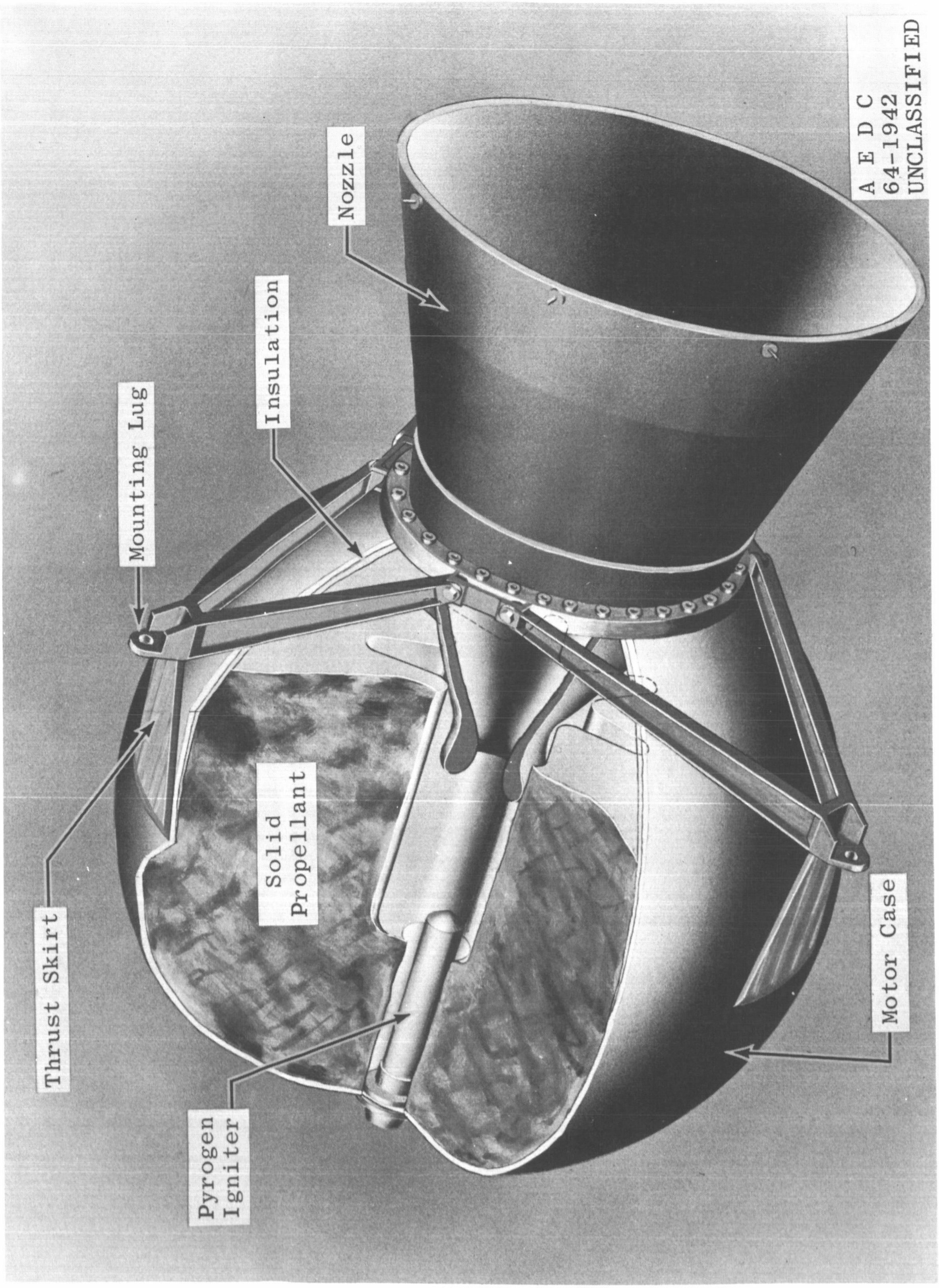
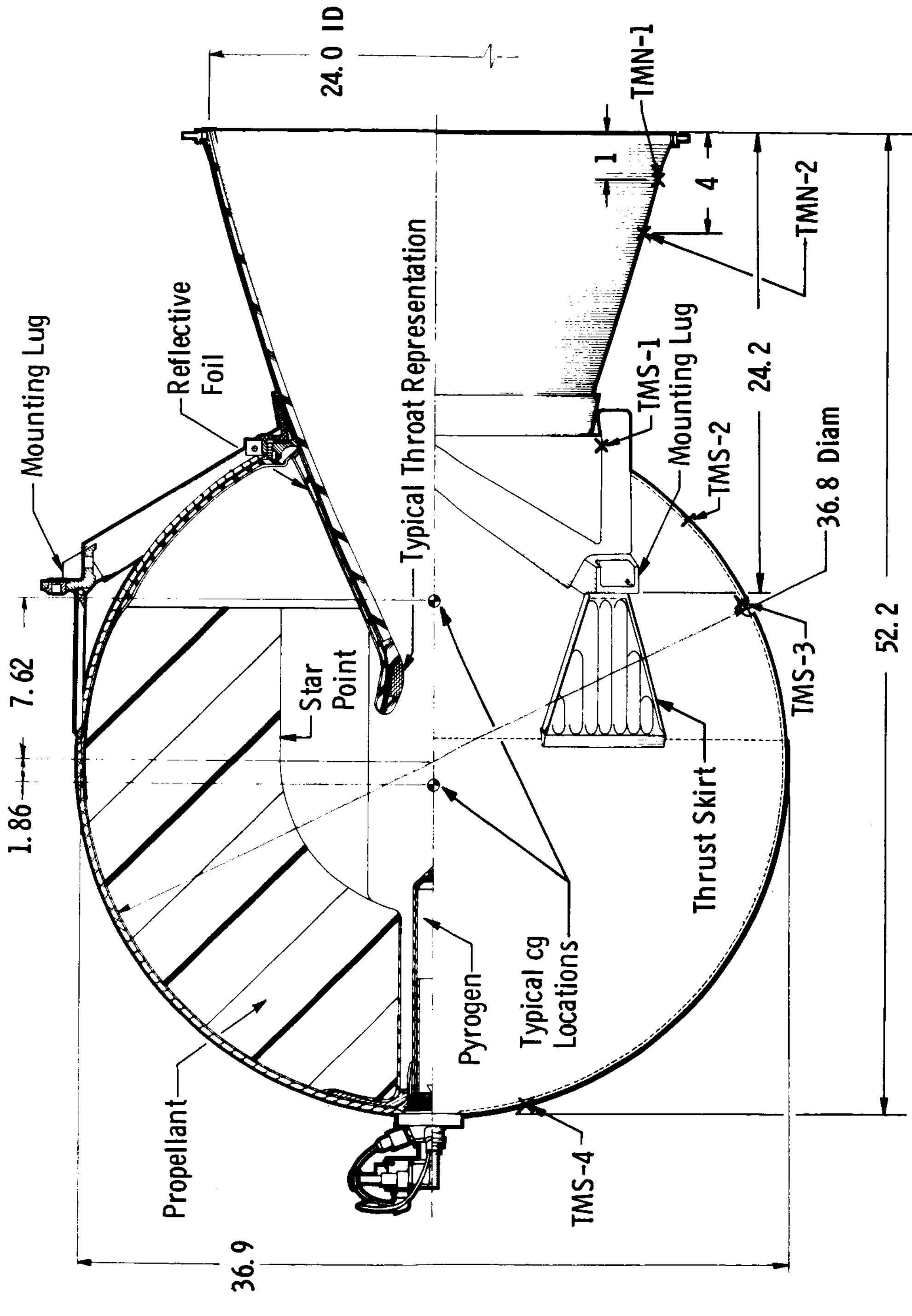


Fig. 2 Isometric Cutaway View of TE-364 (Surveyor Main Retro-Rocket Motor)



All dimensions are in inches.

Fig. 3 Elevation Cutaway View of TE-364

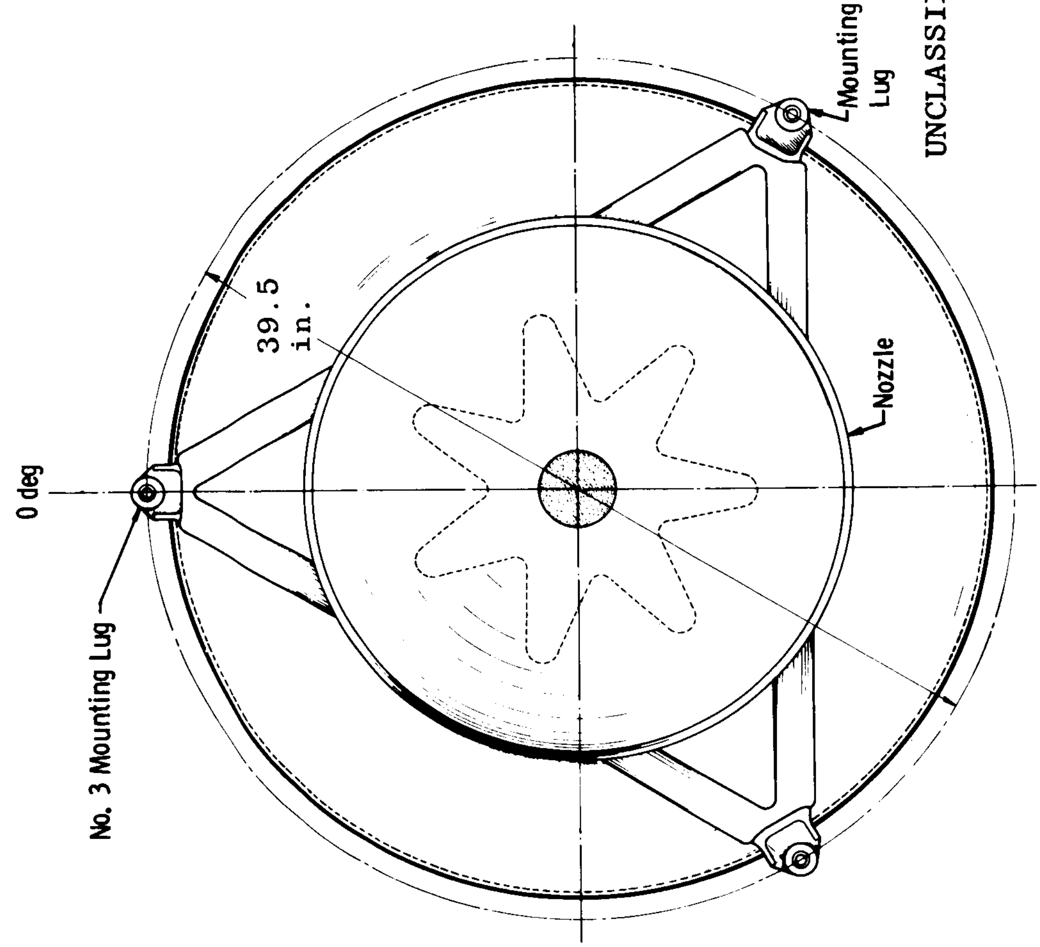
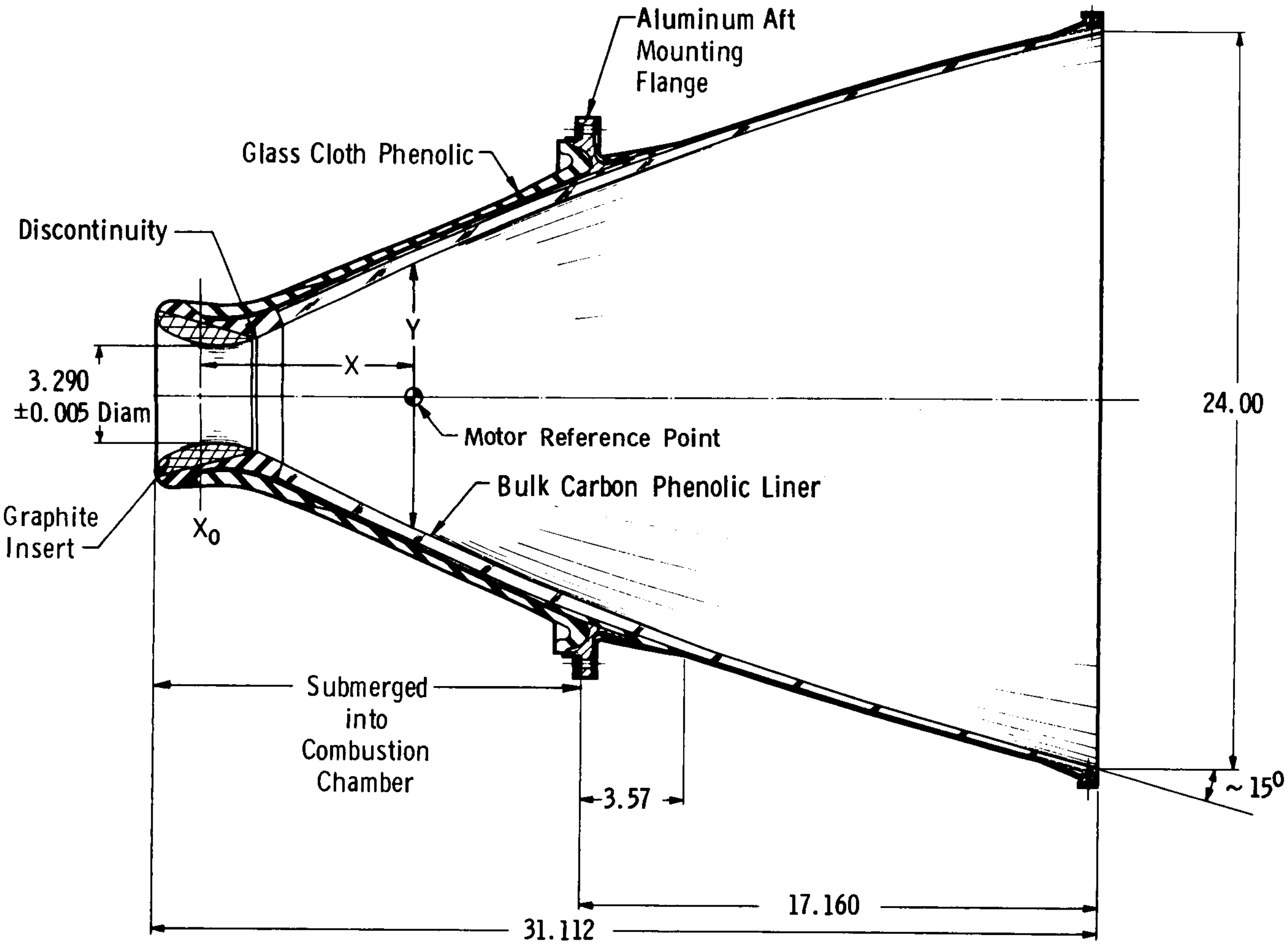


Fig. 4 Head-on View of Motor with Grain Configuration



X	Y
1.500	4.018
2.000	4.510
2.250	4.750
2.750	5.216
3.250	5.680
3.750	6.140
4.250	6.630
5.250	7.560
6.395	8.610
7.834	9.928
9.938	11.750
11.188	12.774
12.557	13.852
14.043	14.970
15.639	16.116
17.342	17.286
19.152	18.468
21.066	19.660
23.082	20.852
25.200	22.042
27.418	23.226
29.112	24.080

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All dimensions are in inches.

Fig. 5 Nozzle with Internal Coordinate Dimensions

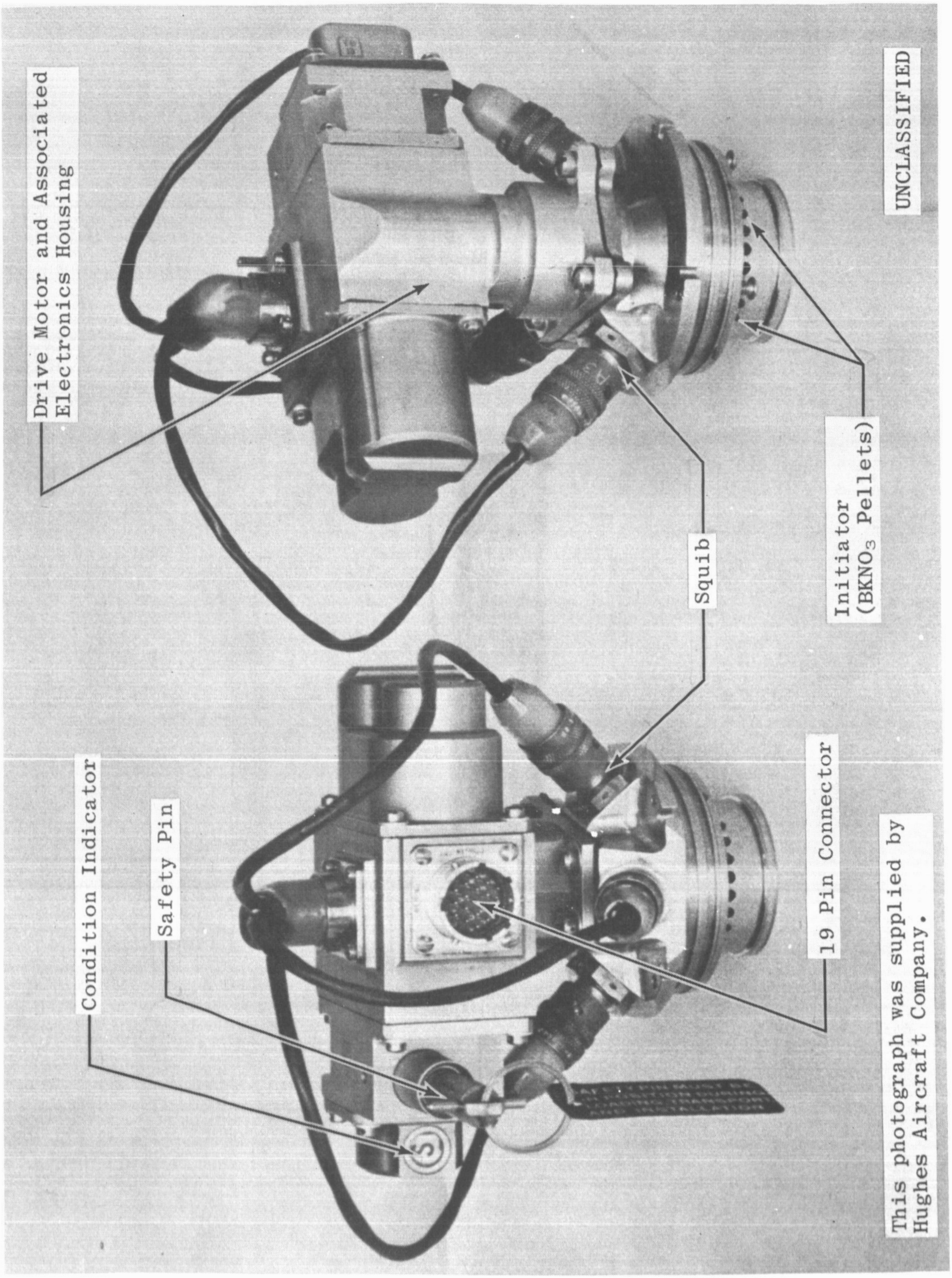
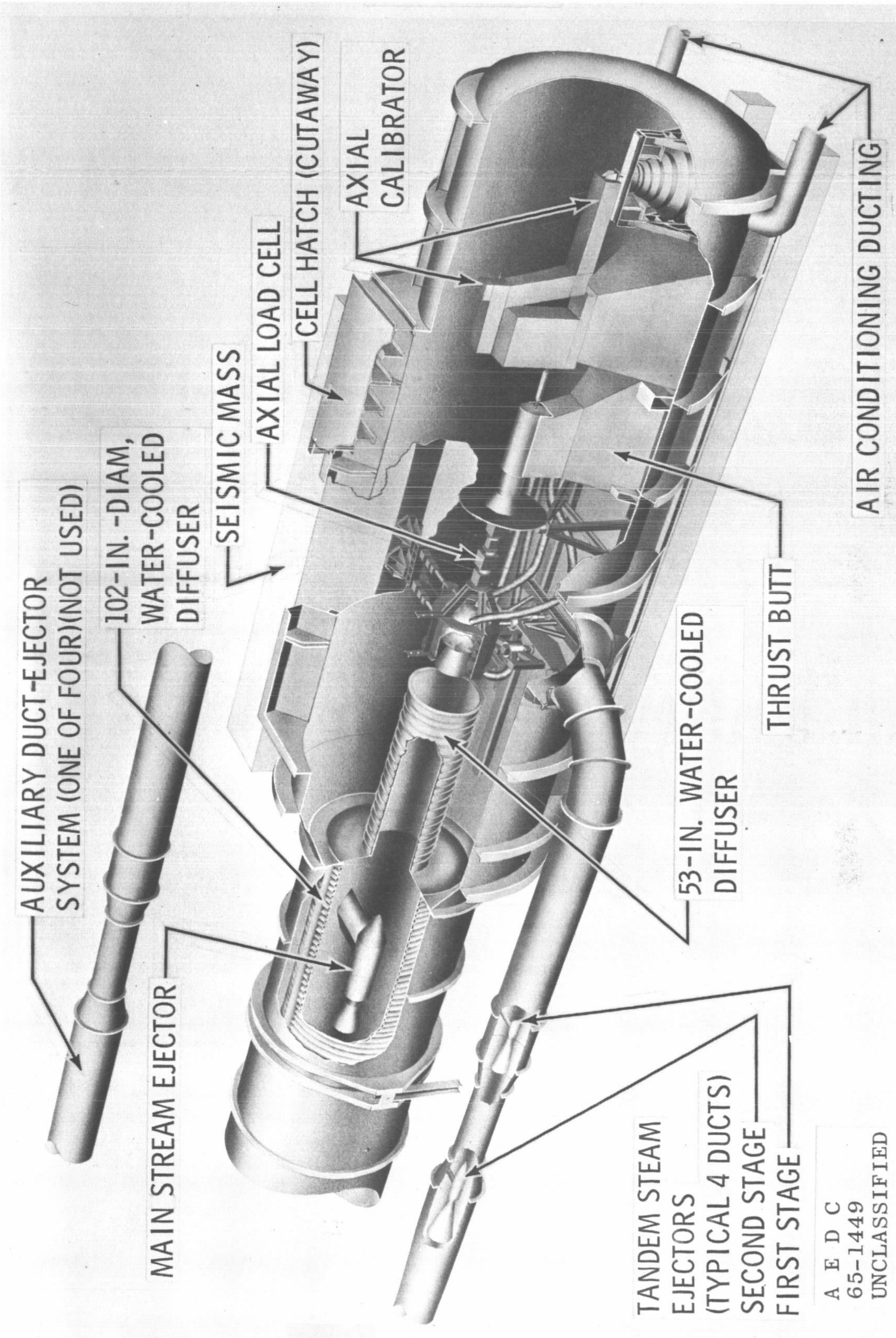
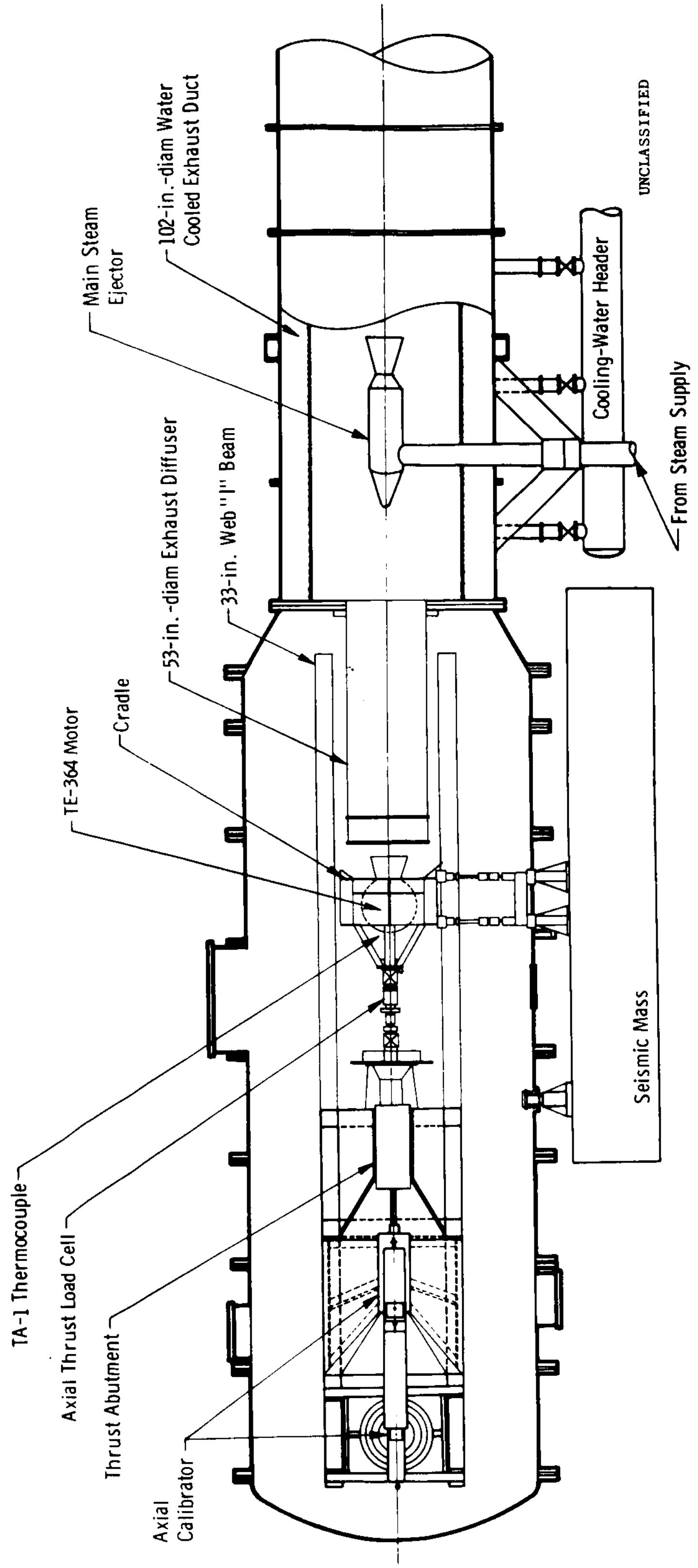


Fig. 6 S/A Mechanism for Surveyor



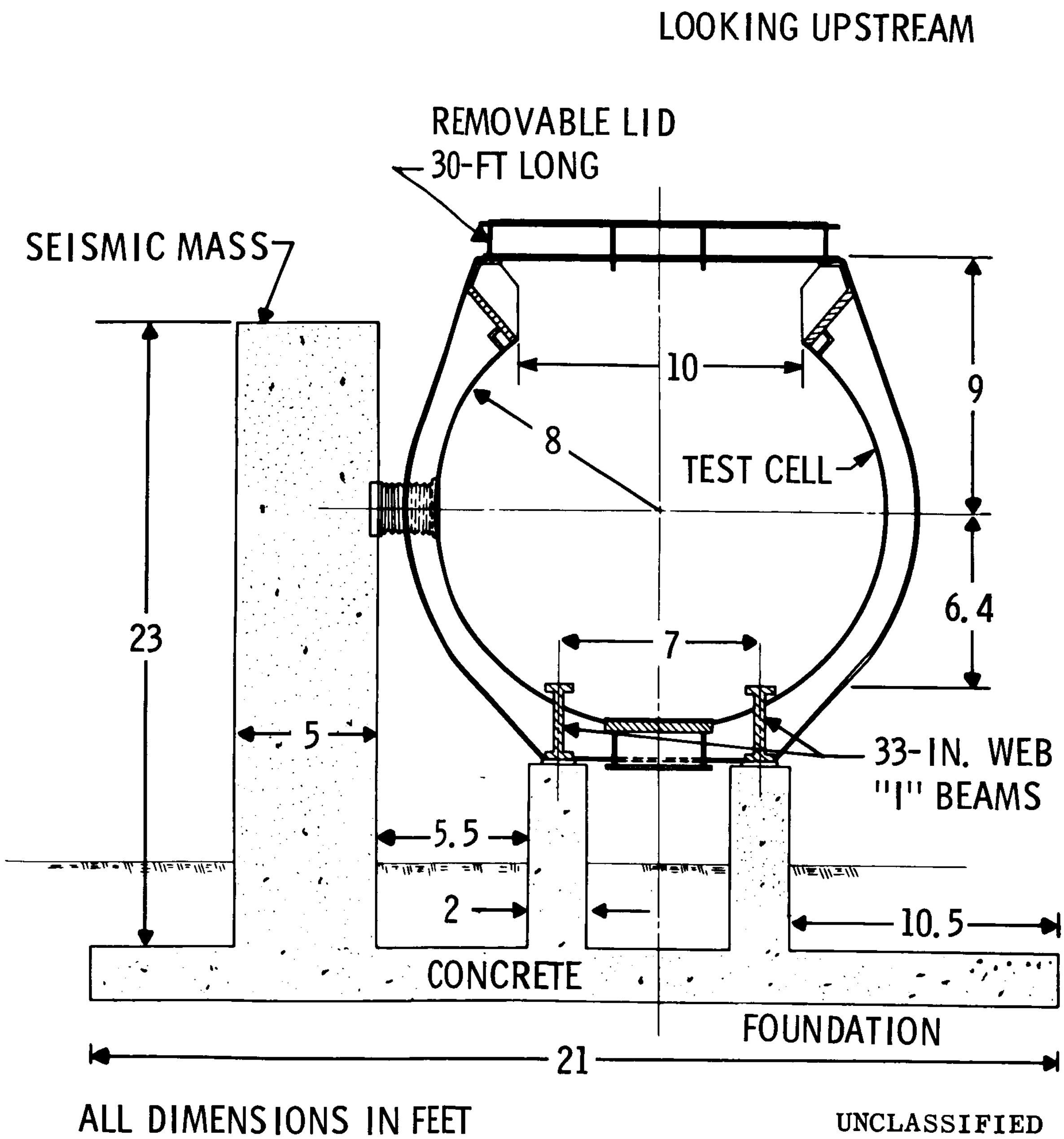
a. Isometric Cutaway View

Fig. 7 Propulsion Engine Test Cell (J-5)



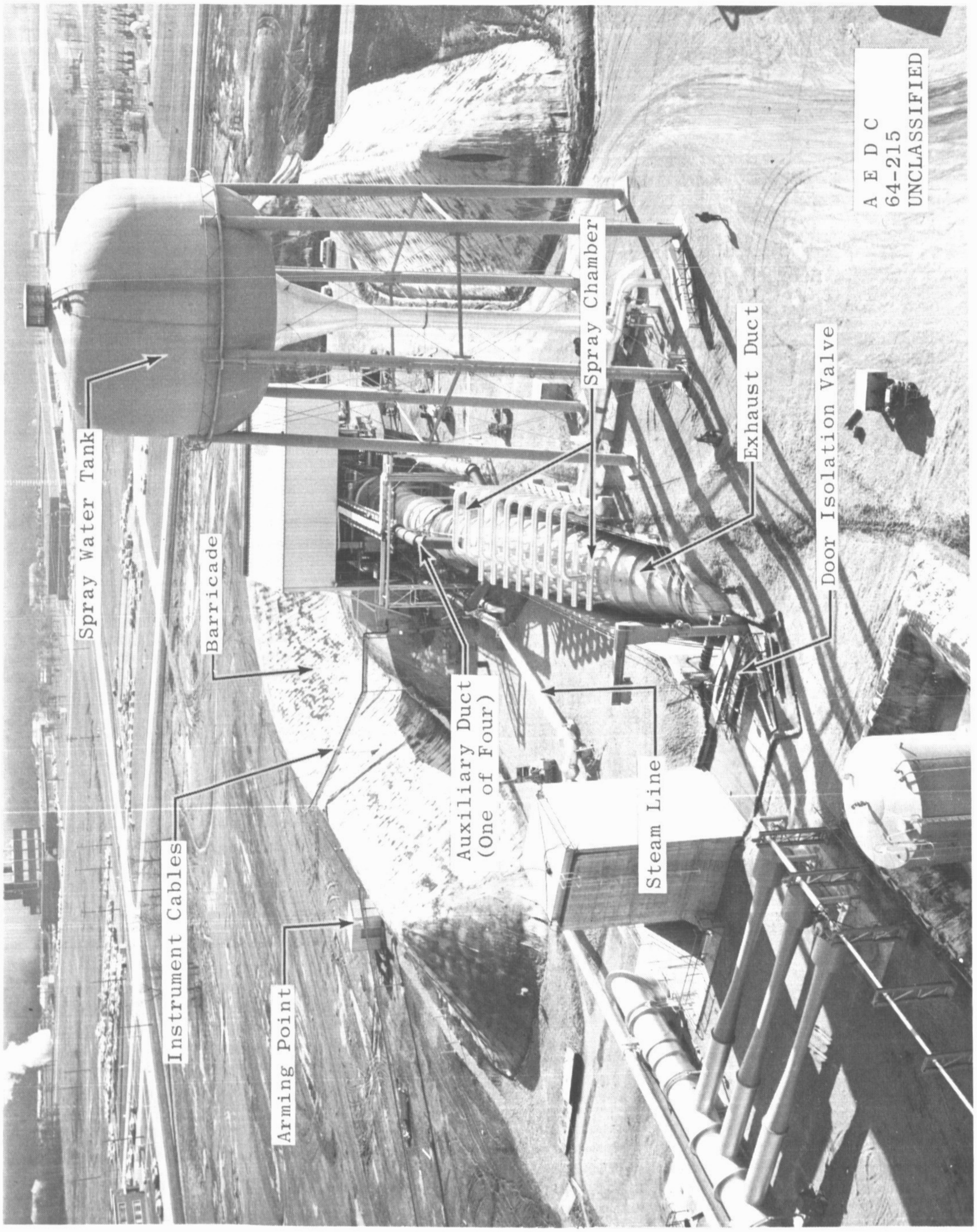
b. Plan View

Fig. 7 Continued



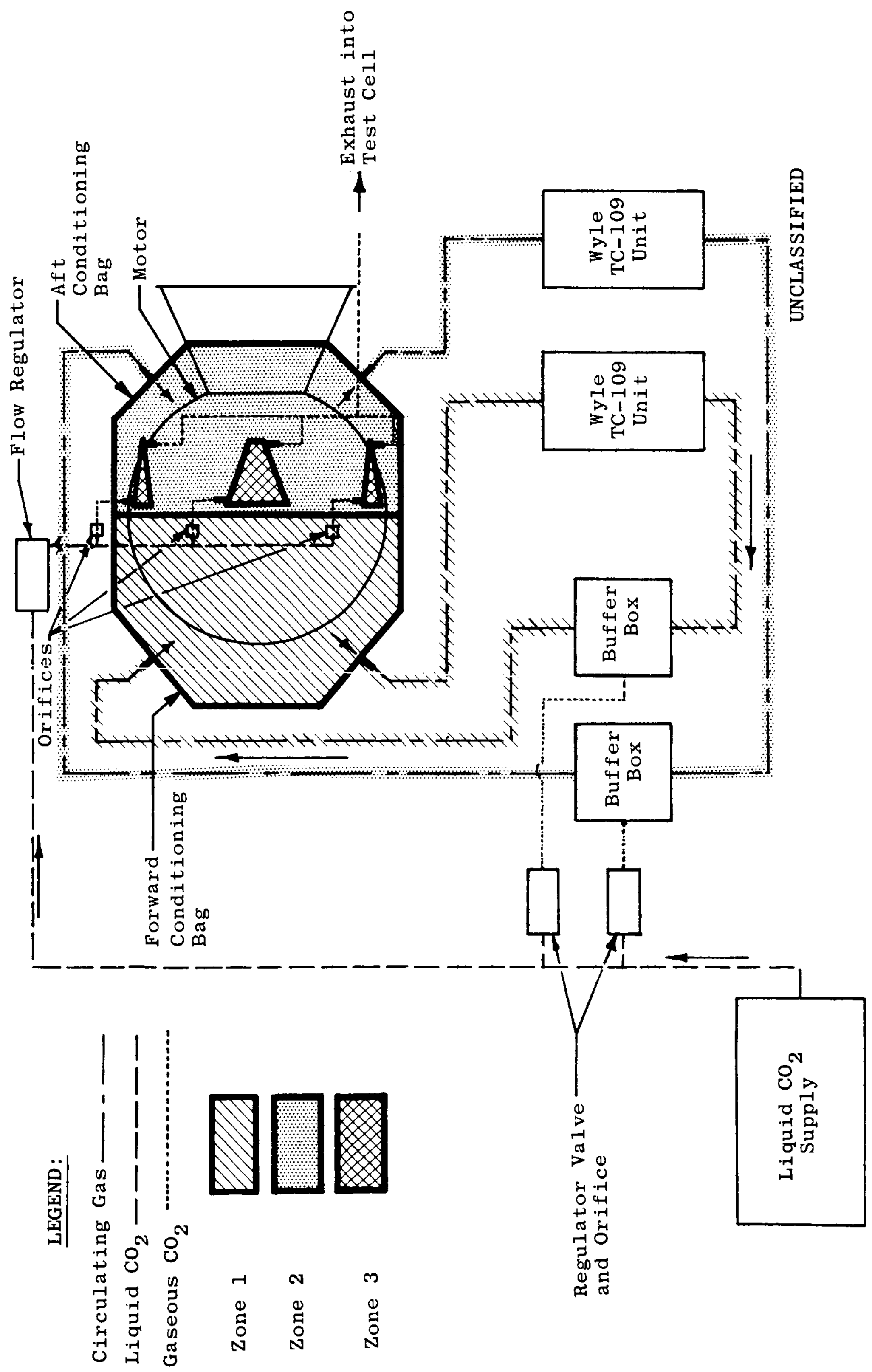
c. End View Looking Upstream

Fig. 7 Continued



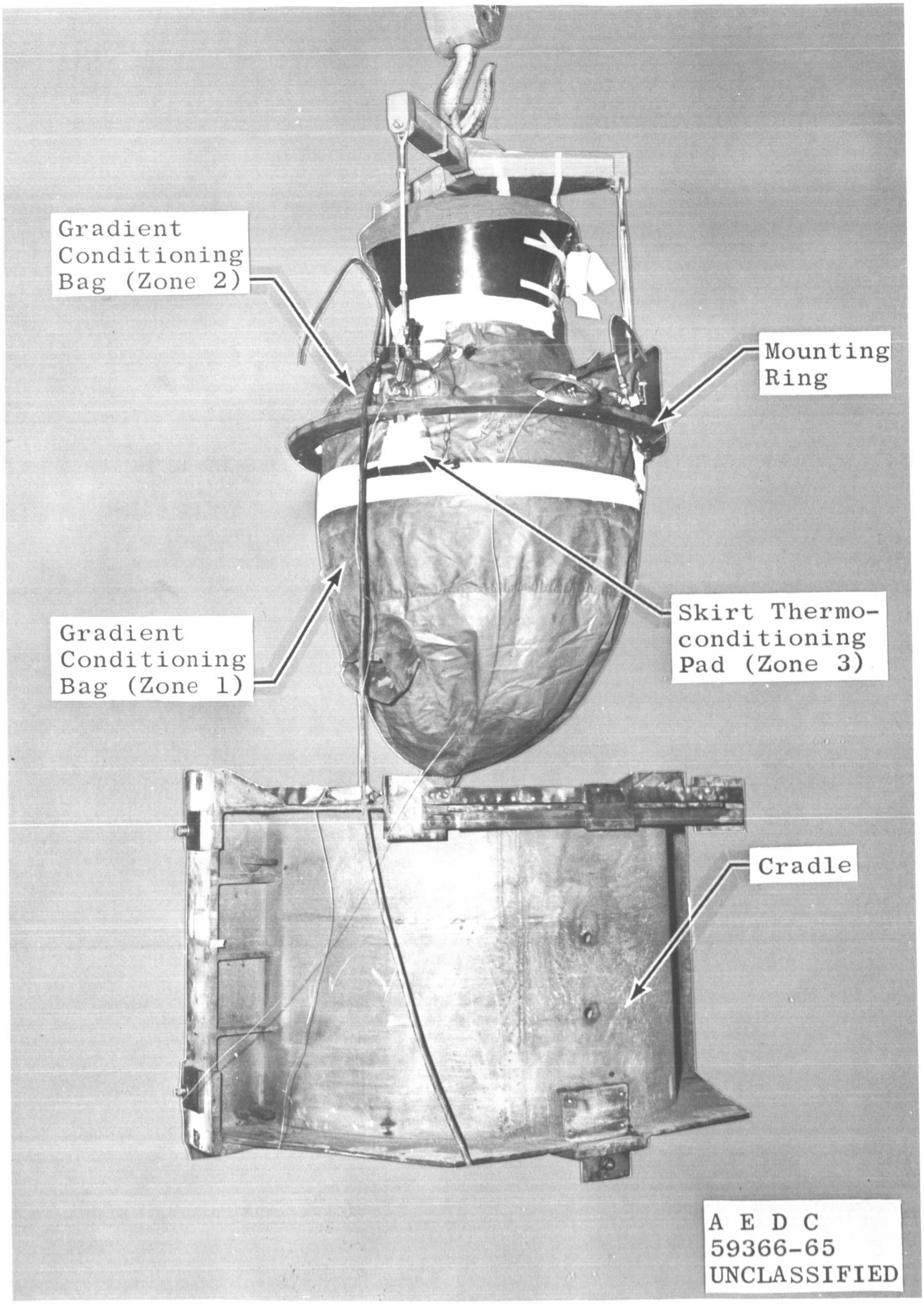
d. Aerial View with Barricade

Fig. 7 Concluded



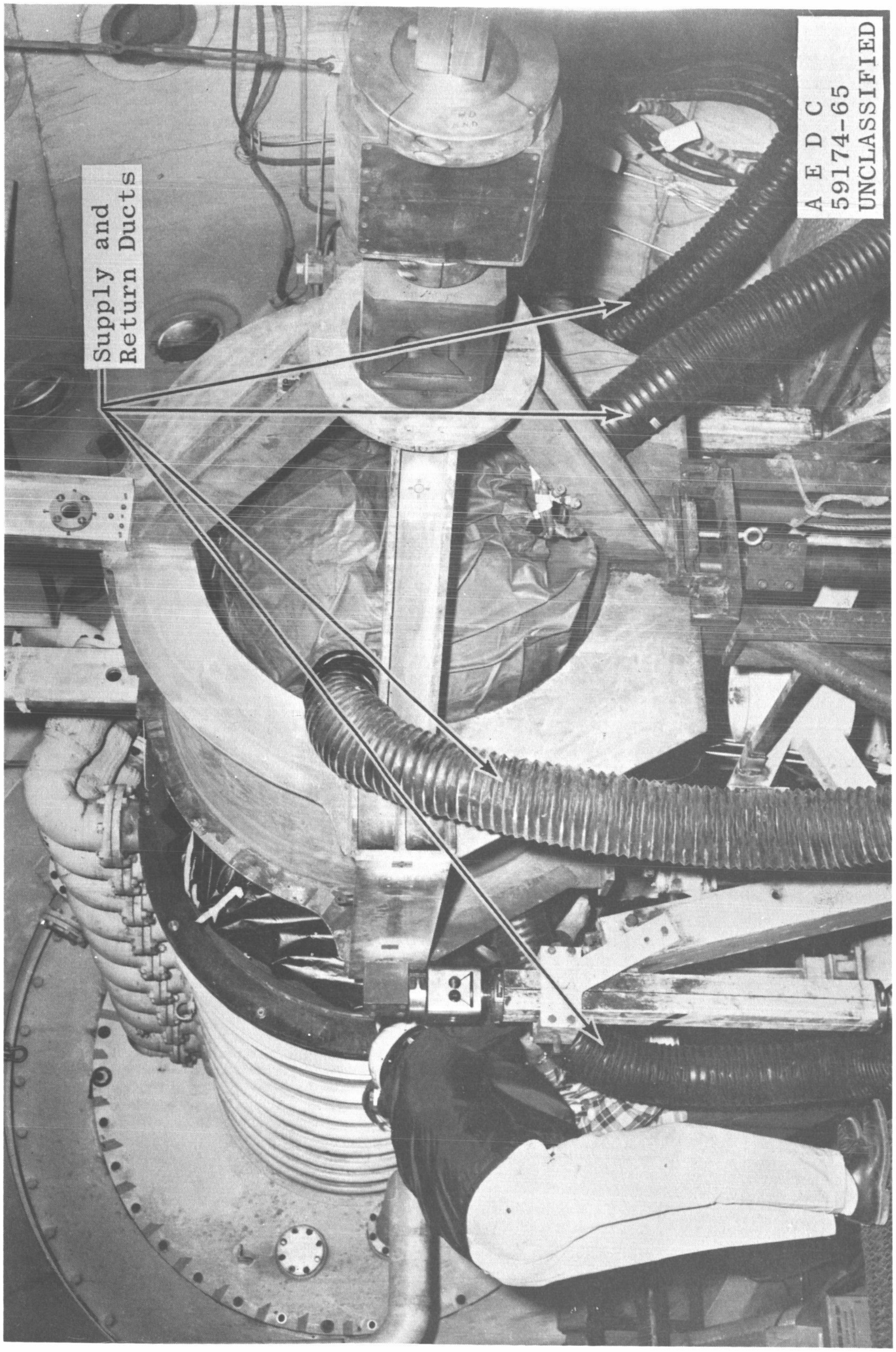
a. Flow Schematic

Fig. 8 Thermal Gradient Conditioning System



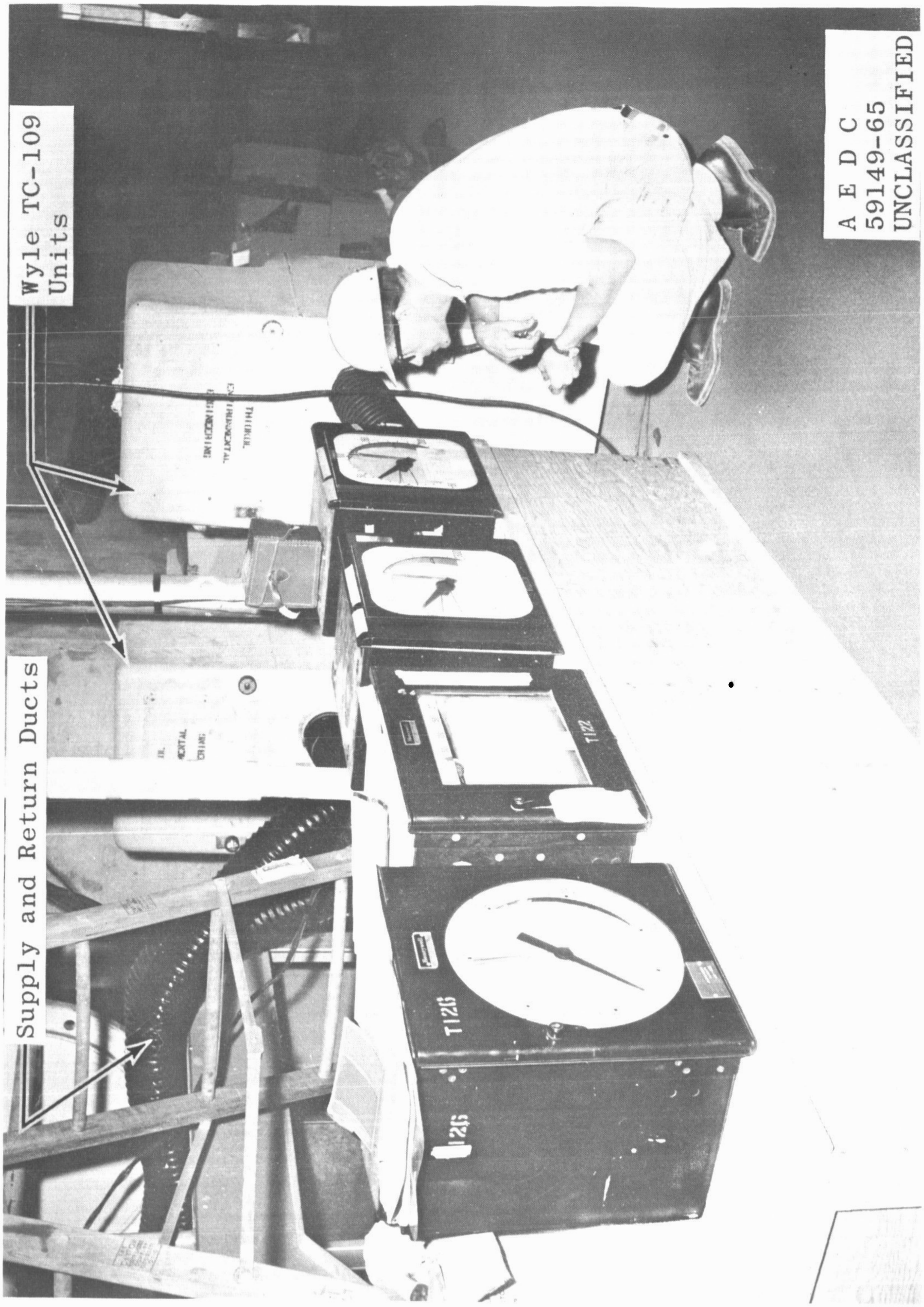
b. Motor with Conditioning Bag (Tent) with Cradle

Fig. 8 Continued



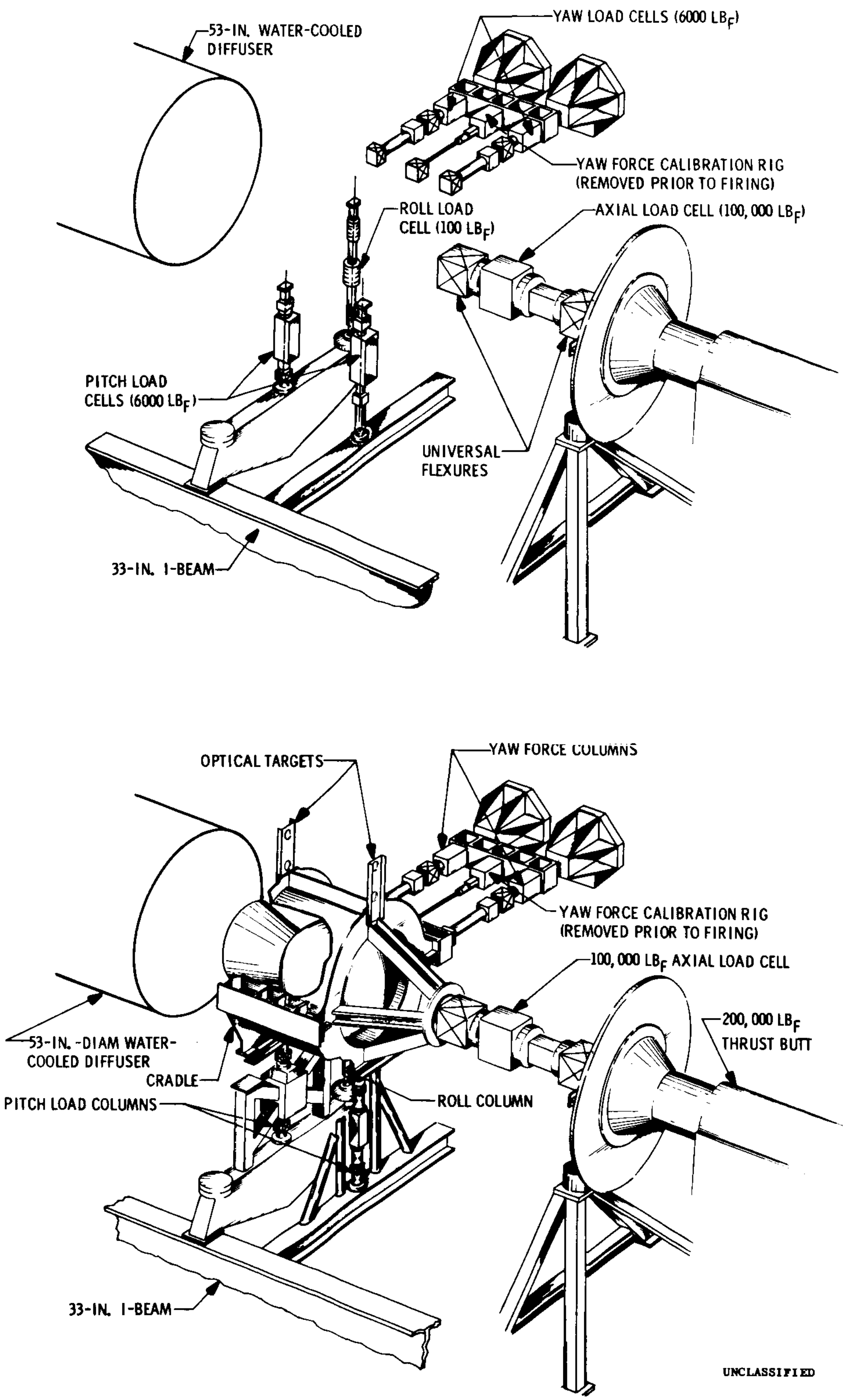
c. Motor/Cradle Installed in Test Cell

Fig. 8 Continued



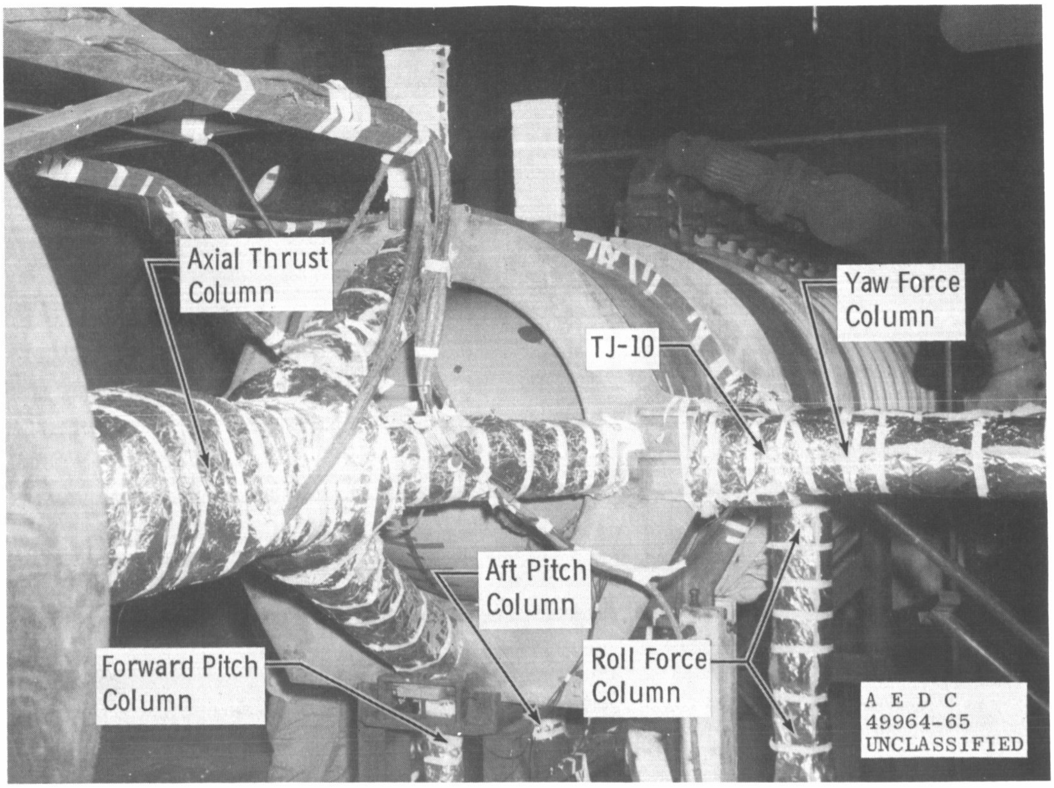
d. Temperature Readout Complex

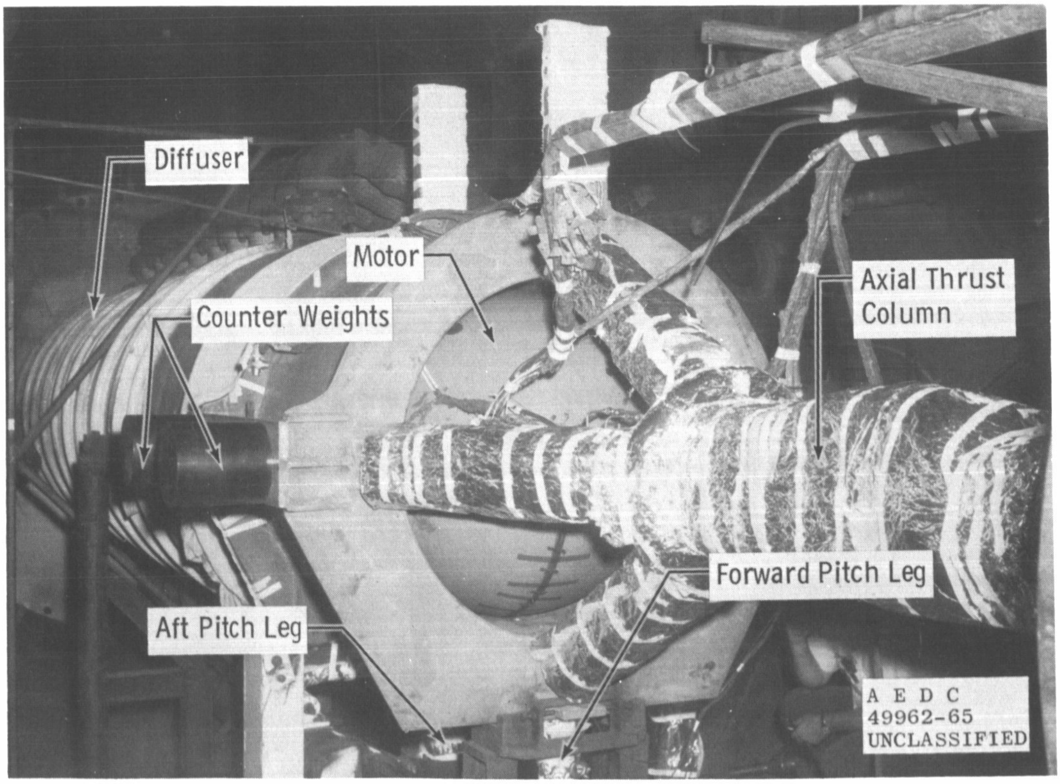
Fig. 8 Concluded



a. Cradle and Force/Support Links

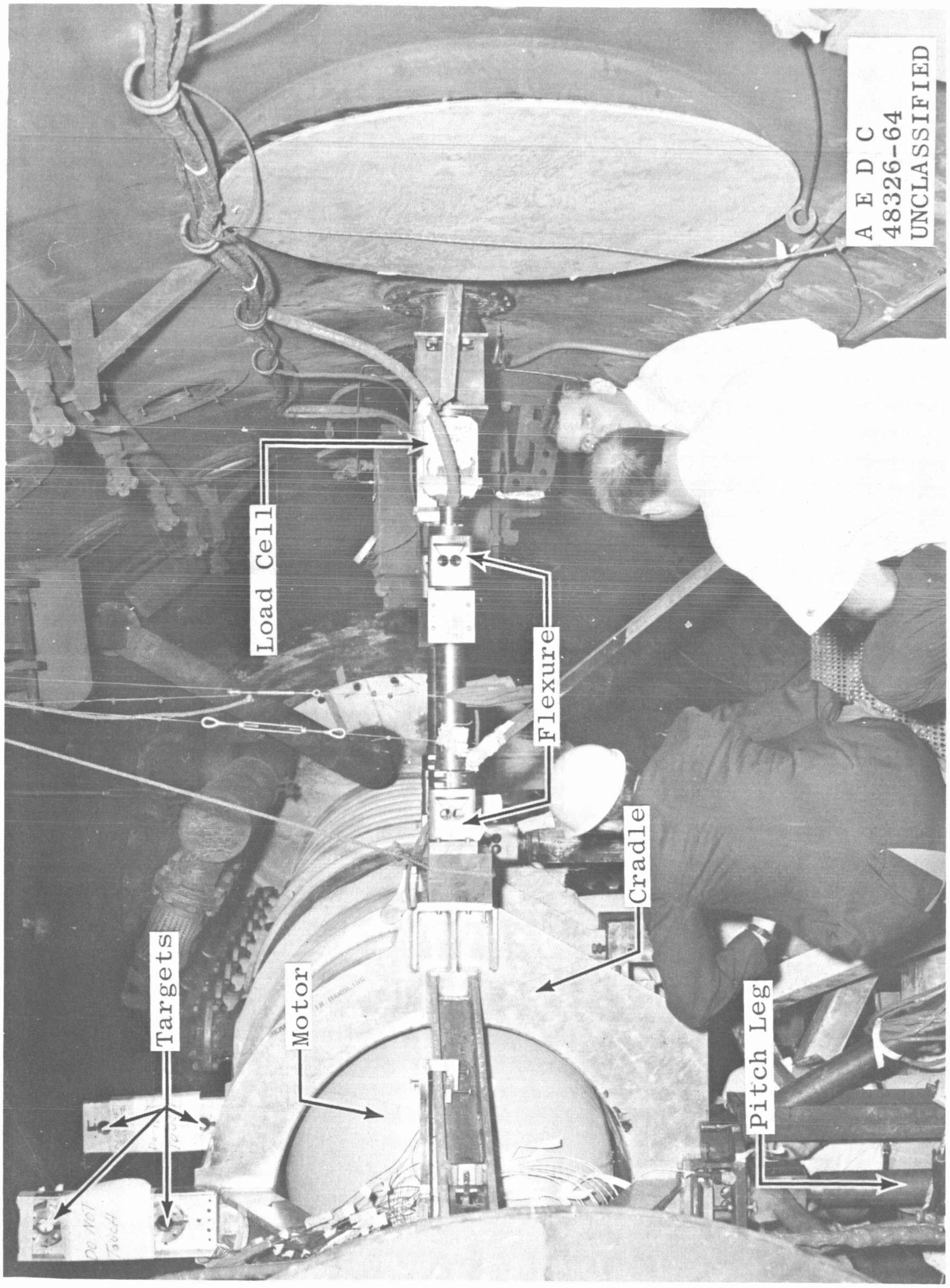
Fig. 9 Thrust Hardware





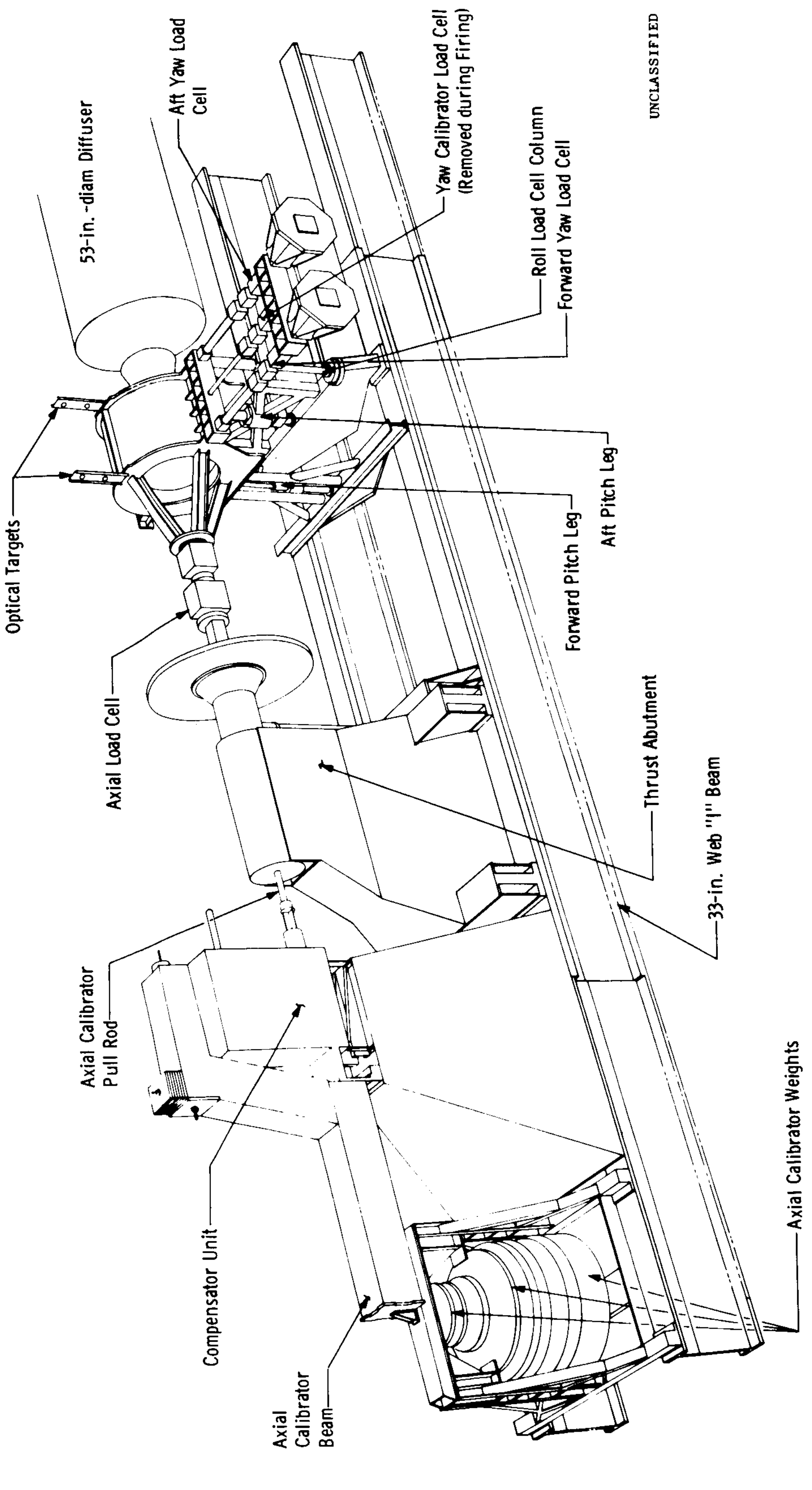
b. Photographs with Insulation and Counterweights

Fig. 9 Continued



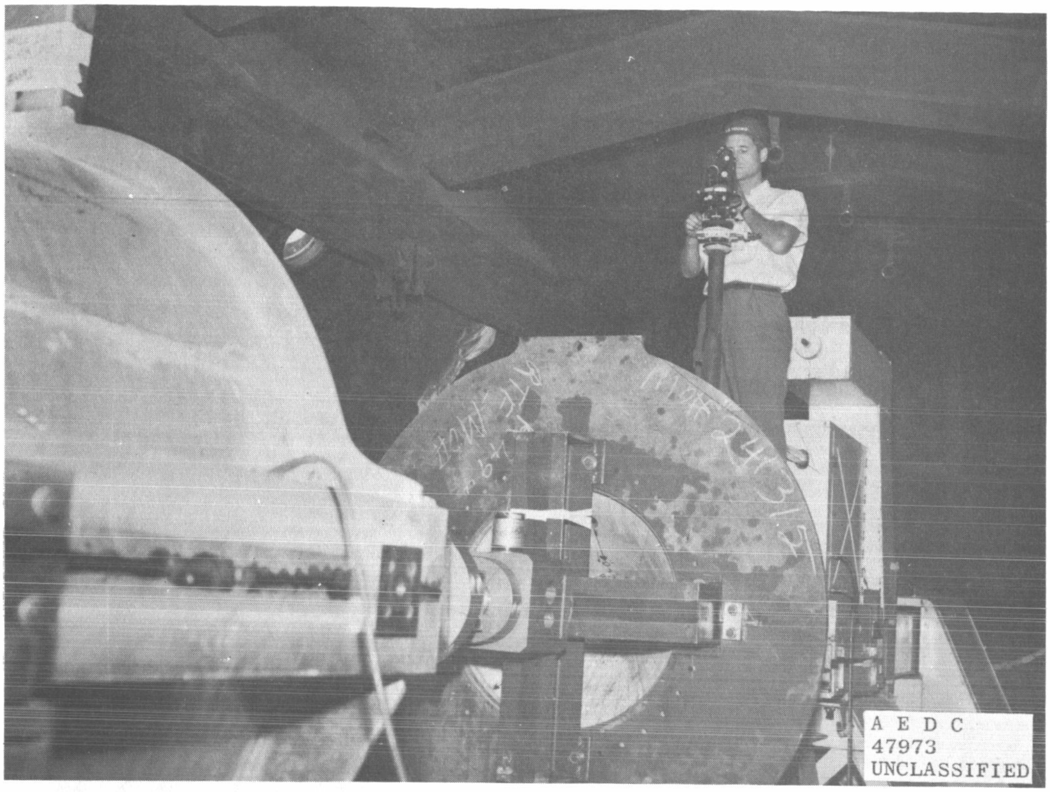
c. Yaw Columns with Load Cells and Flexures

Fig. 9 Continued



d. Isometric View with Axial Calibrator

Fig. 9 Concluded



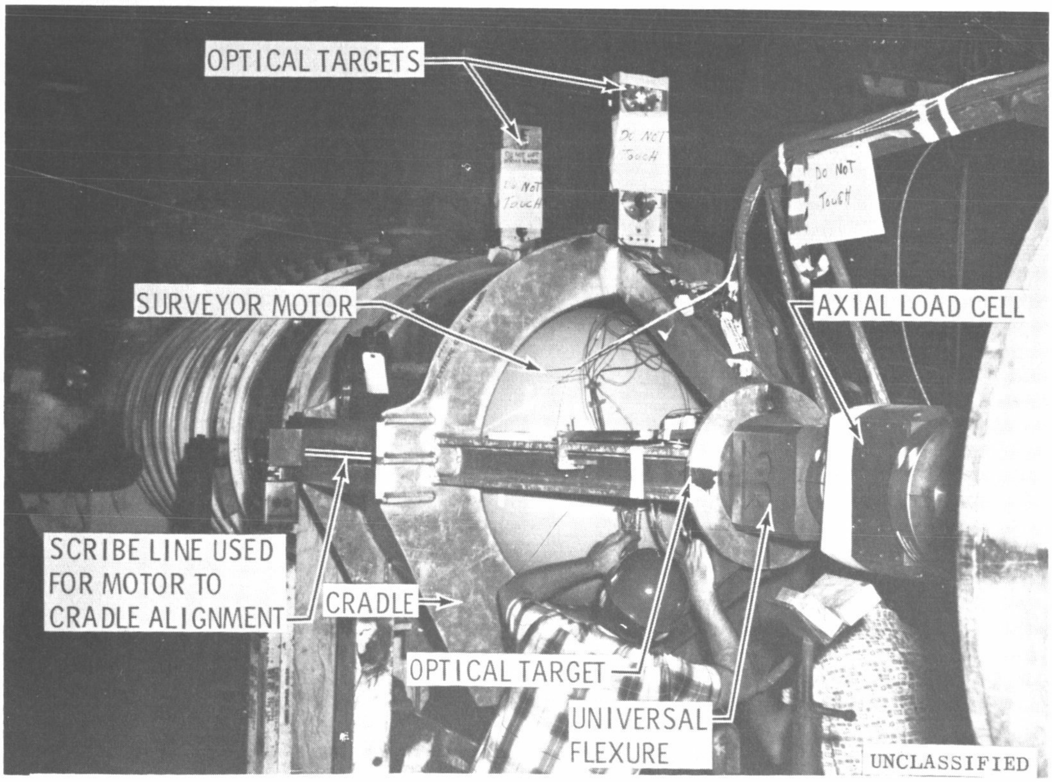


Fig. 10 Hardware Alignment

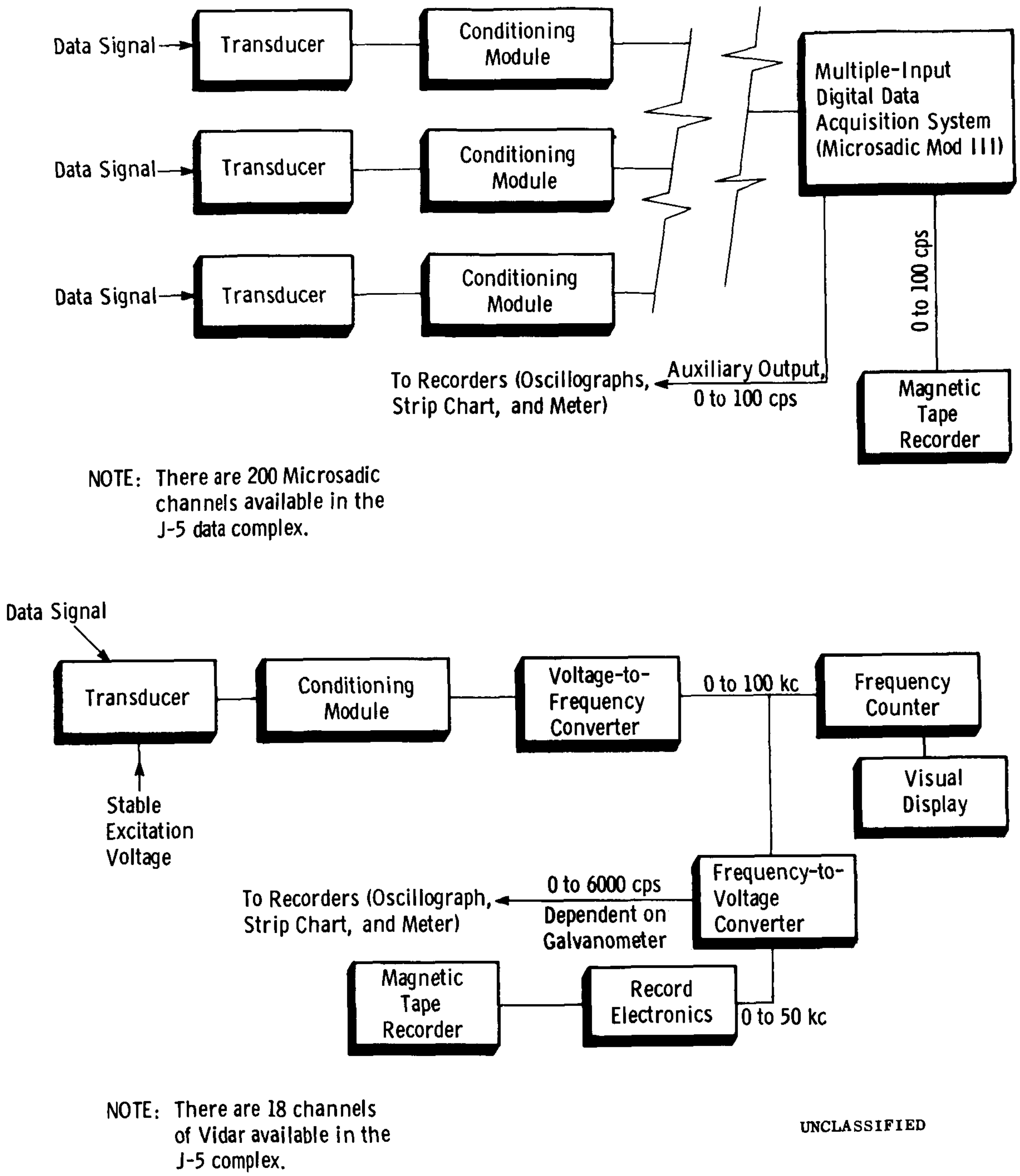


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Fig. 11 Schematic of Digital Data Systems

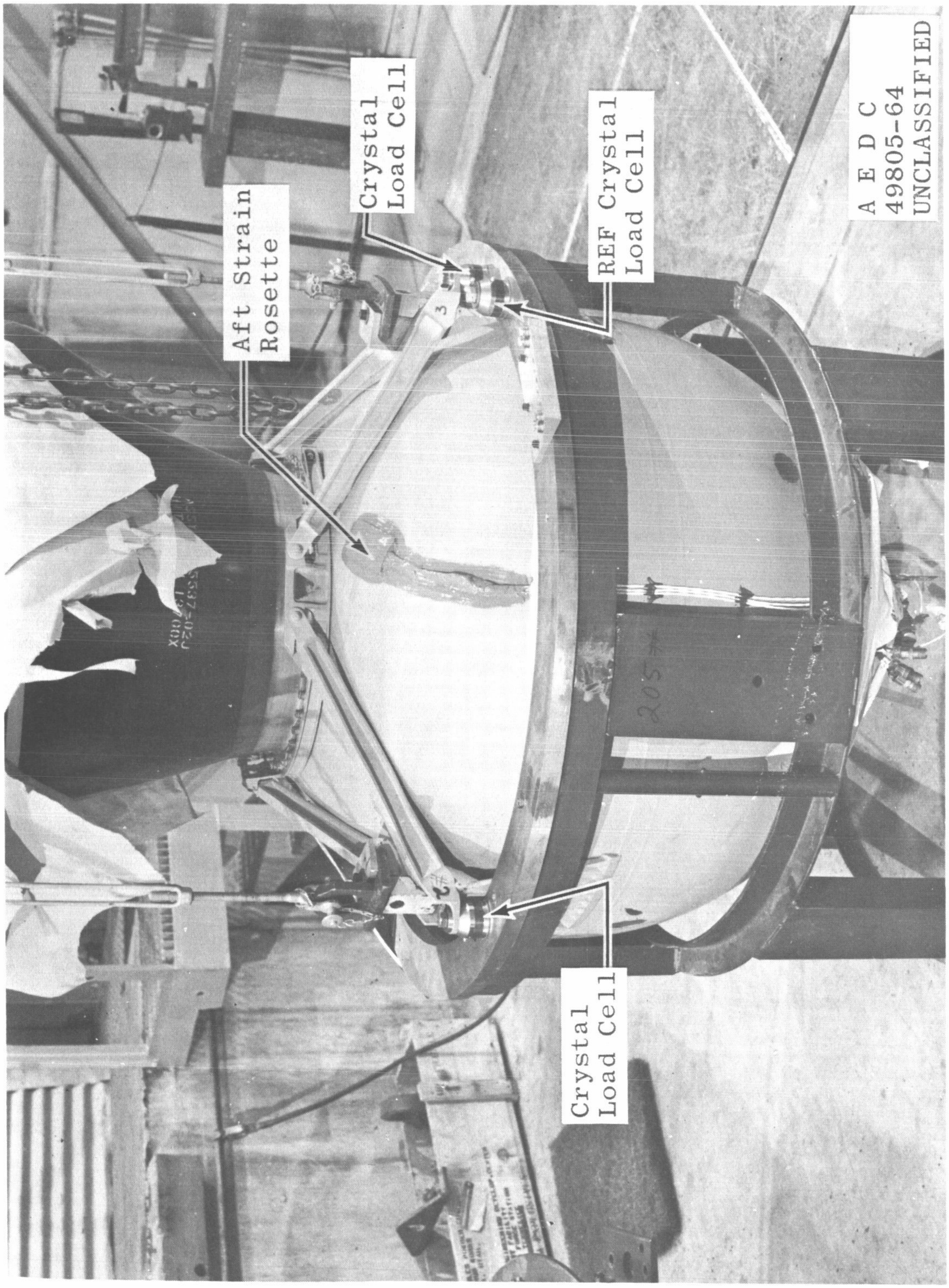
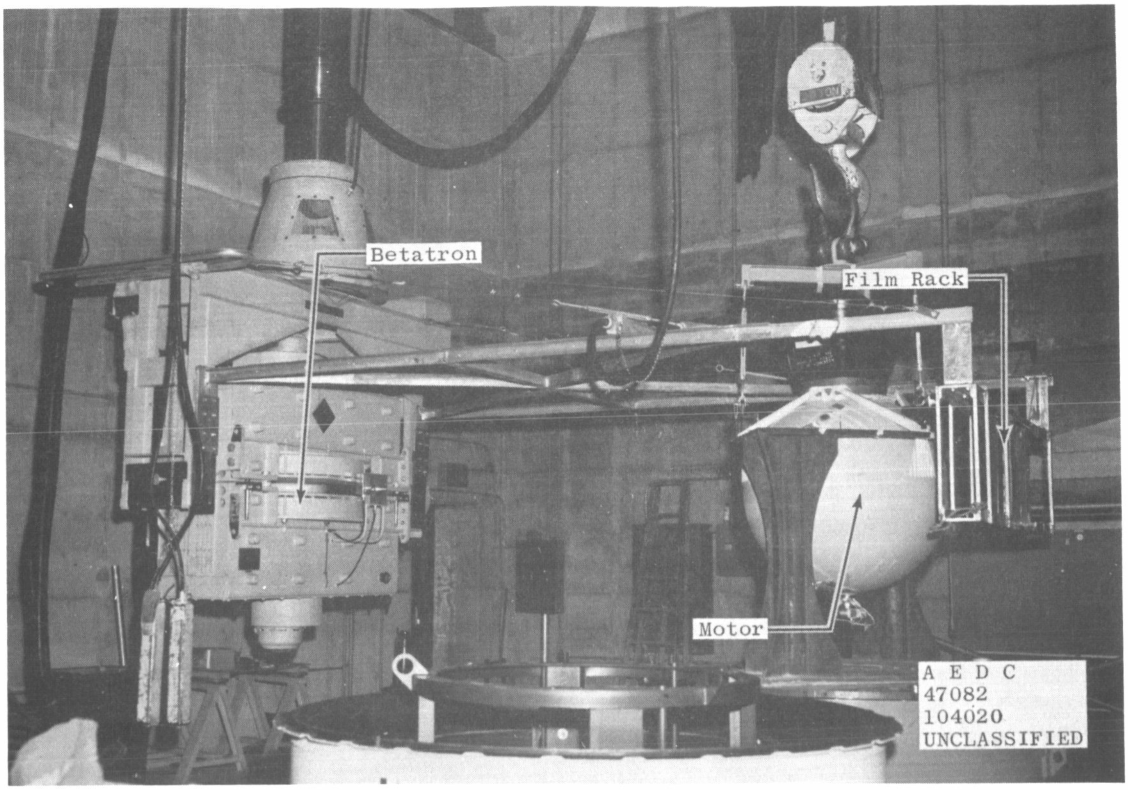


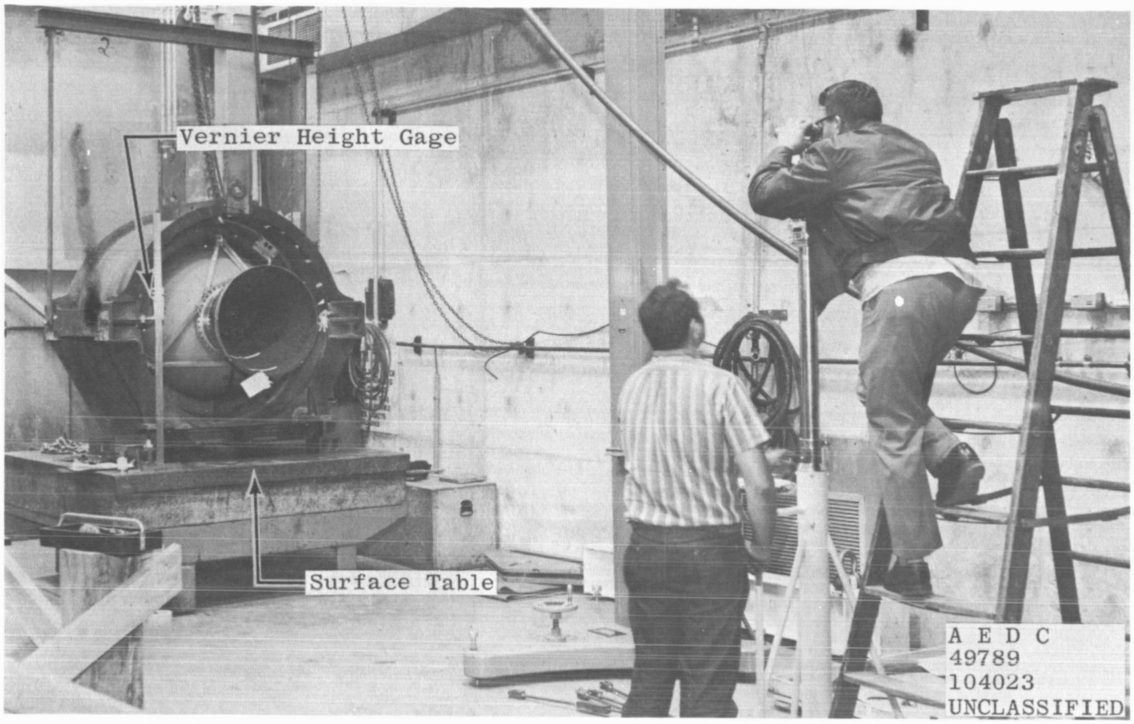
Fig. 12 Pre-Fire Motor with Instrumentation



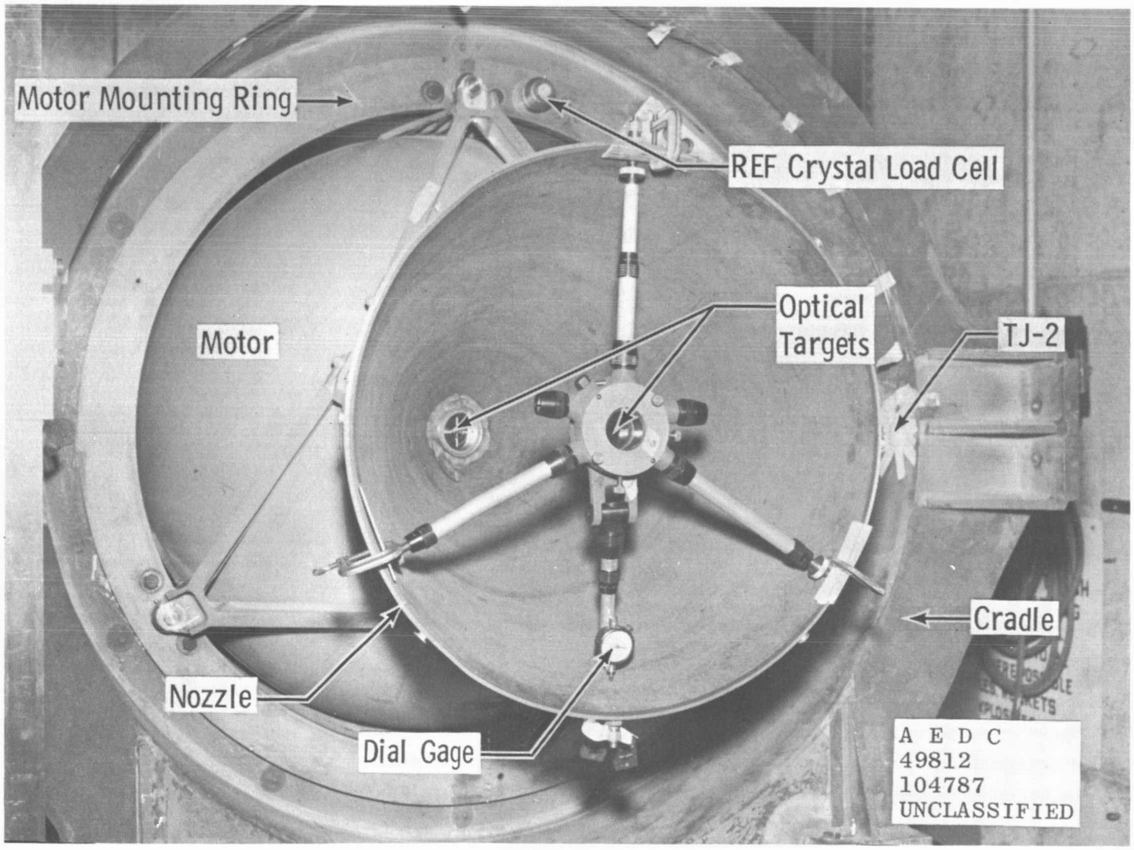
a. Typical Motor at X-Ray

b. Loading into Cradle

Fig. 13 Motor Handling Views



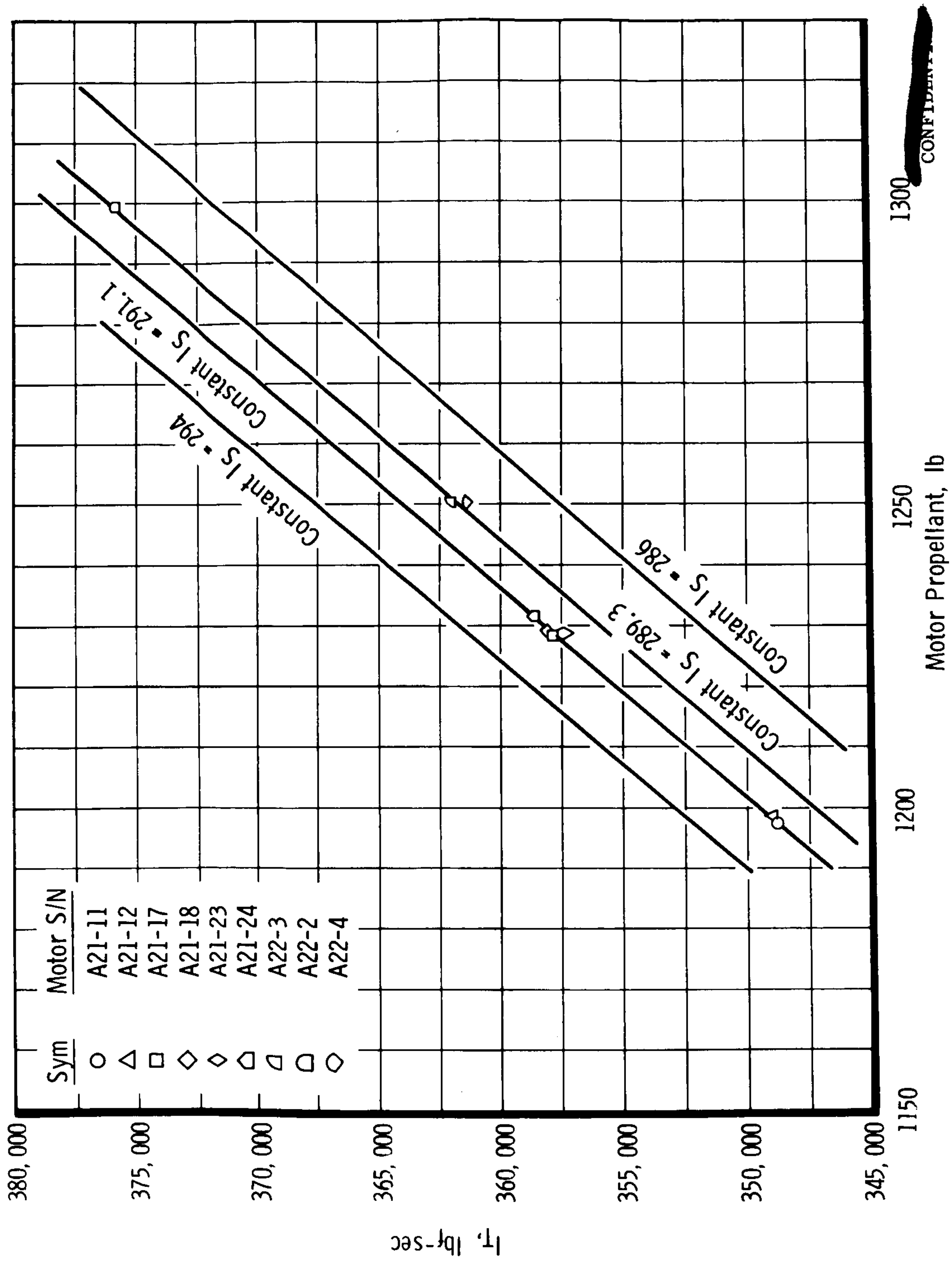
a. Placing on Surface Table



b. Nozzle Target Installation

Fig. 14 Motor-to-Cradle Alignment

[redacted]

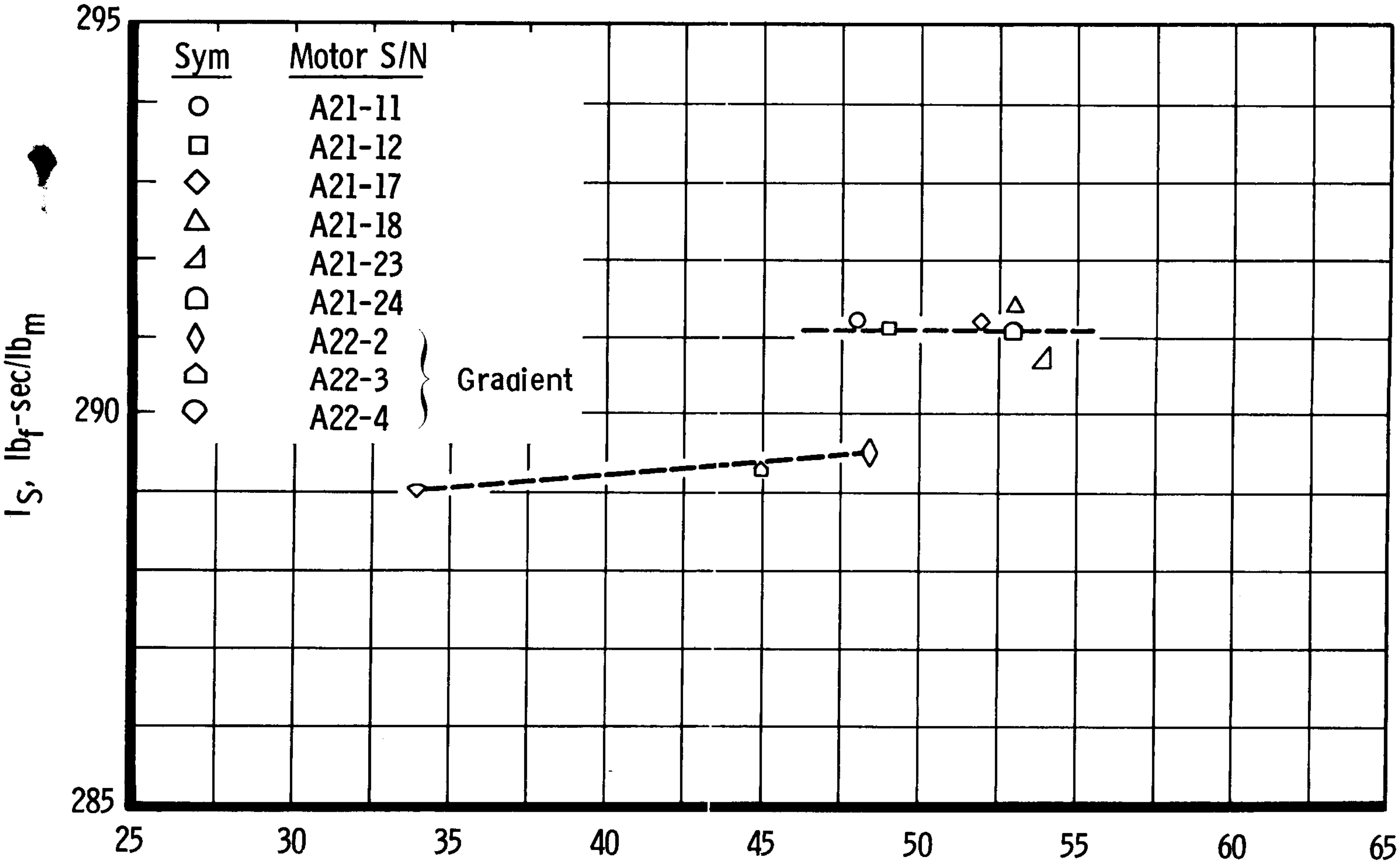


a. Constant I_S Lines

Fig. 15 Motor Performance Data (Calculated)

[redacted]

[redacted]

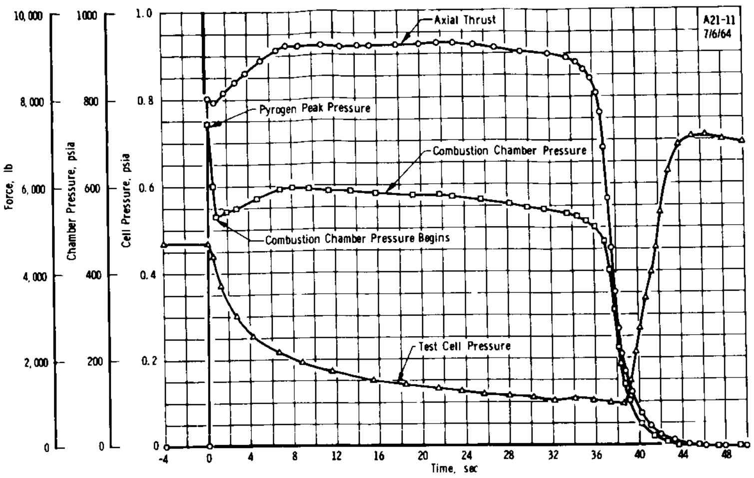


Propellant Grain Temperature, ^{0}F

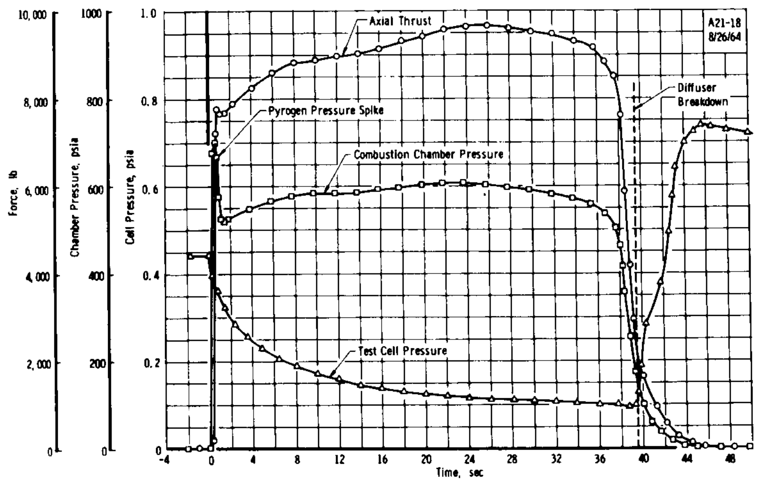
[redacted]

b. I_s versus Grain Temperature

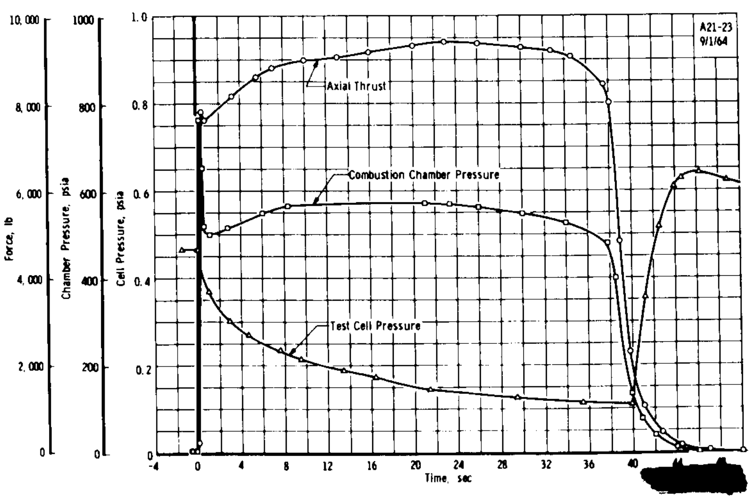
Fig. 15 Concluded



a. Typical 1200-lb Motor

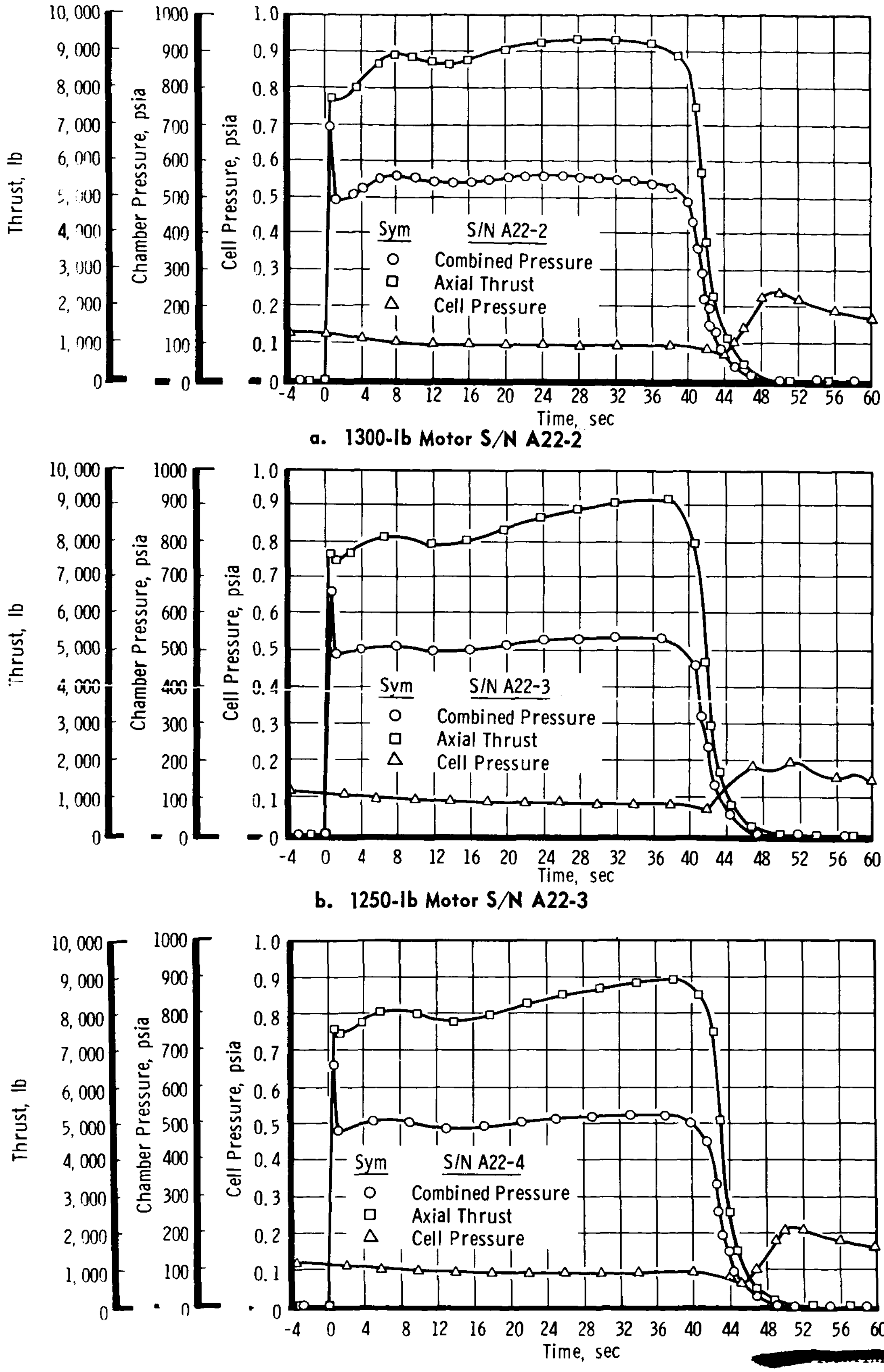


b. Typical 1230-lb Motor



c. 1230-lb Motor with Lowest Performance

Fig. 16 Motor Performance Plots (Measured)



a. 1300-lb Motor S/N A22-2

b. 1250-lb Motor S/N A22-3

c. 1250-lb Motor S/N A22-4

Fig. 17 Motor Performance Plots (Measured)

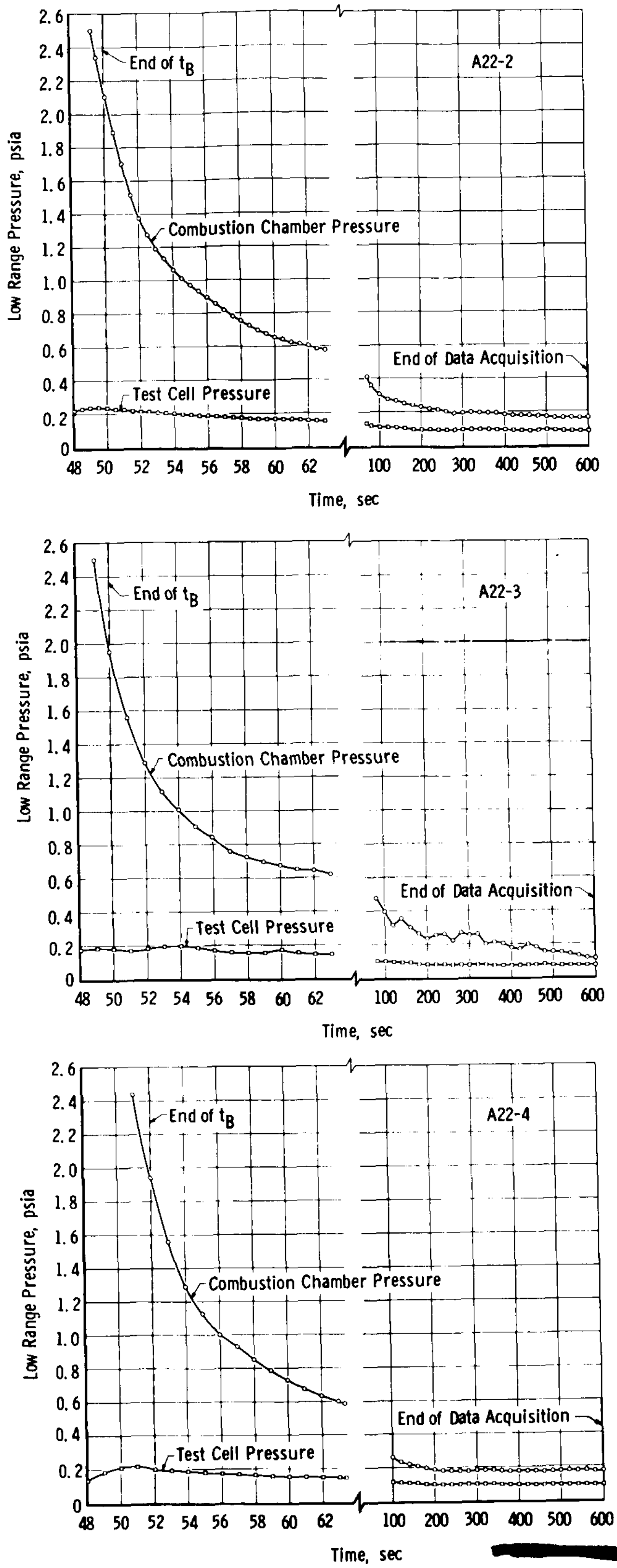
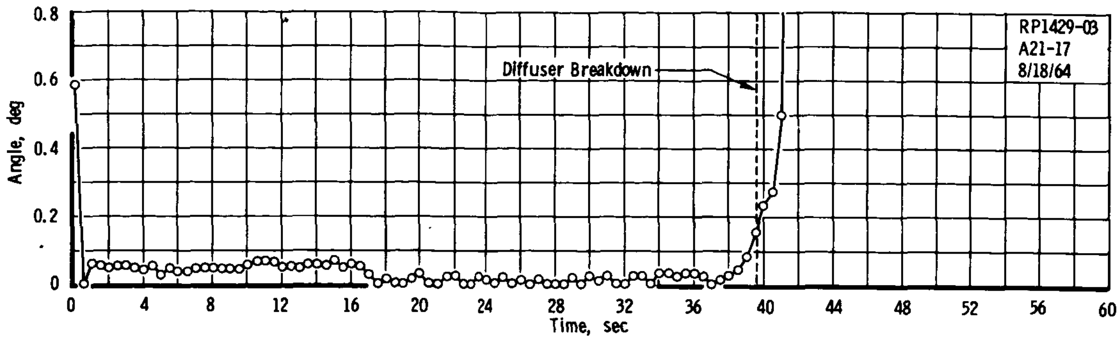
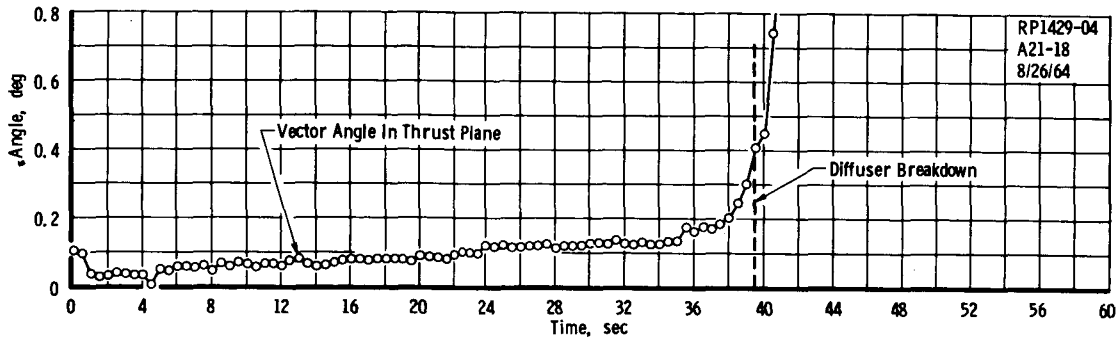


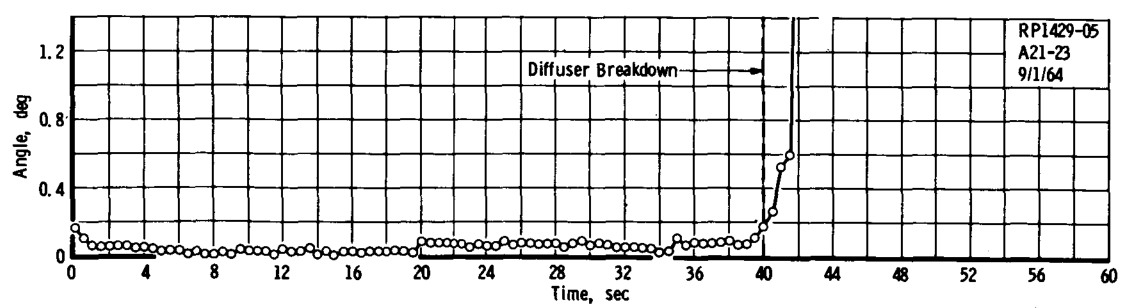
Fig. 18 Comparison of Low-Range Combustion Pressure Outgassing



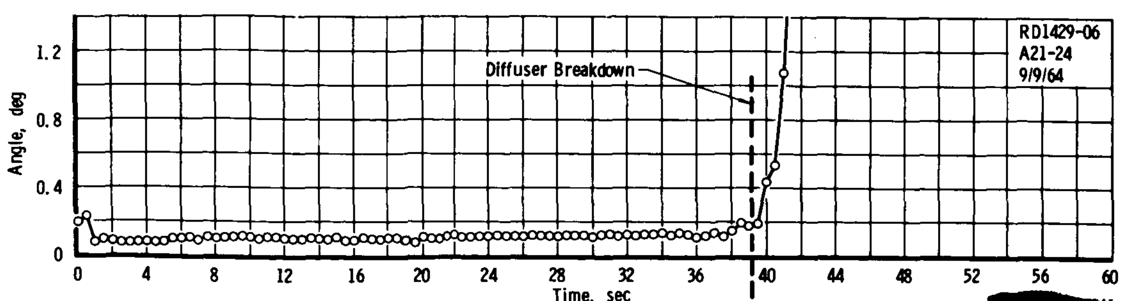
a. S/N A21-17



b. S/N A21-18



c. S/N A21-23



d. S/N A21-24

Fig. 19 Thrust Vector Excursion Angle in Thrust Plane

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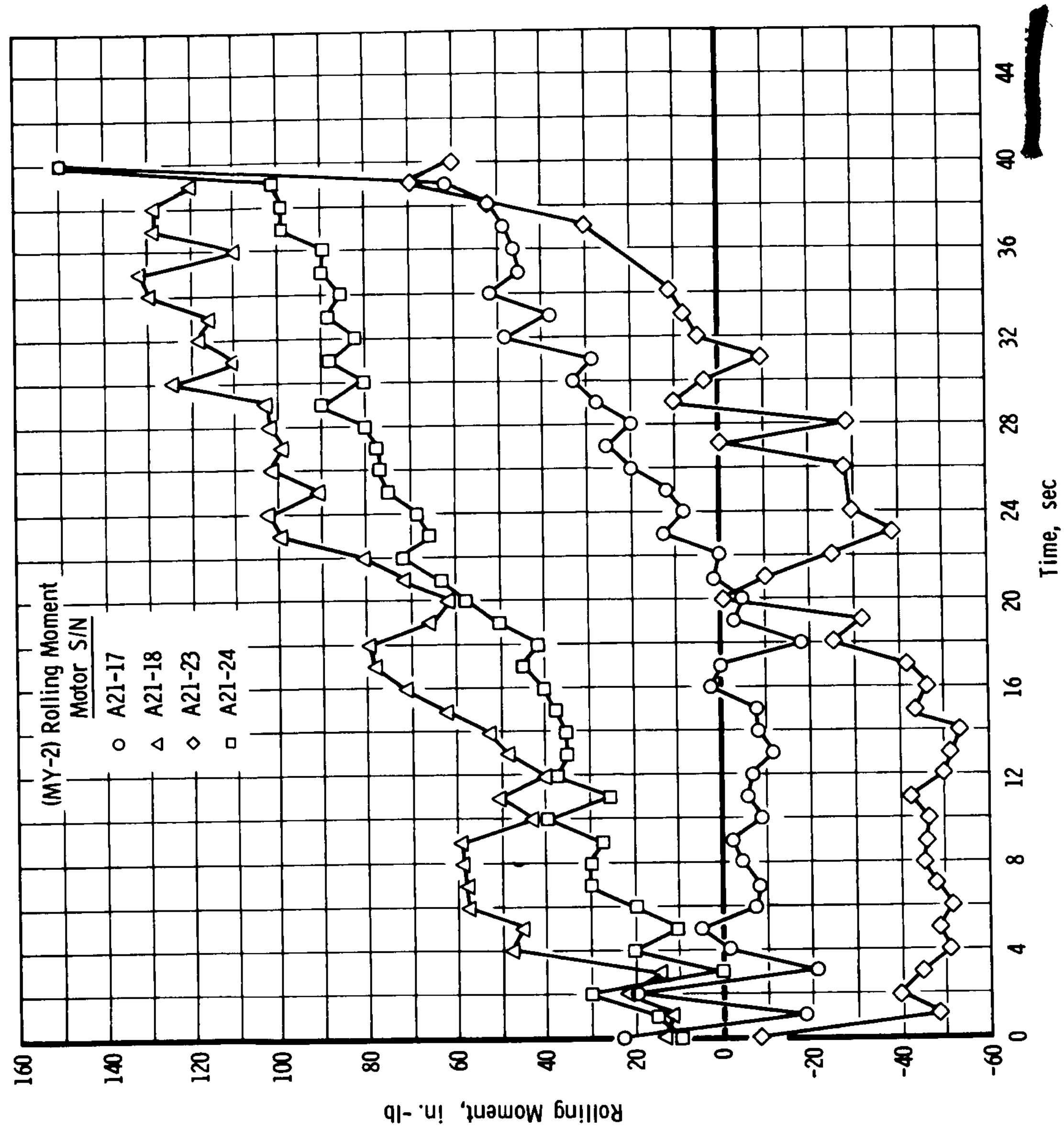
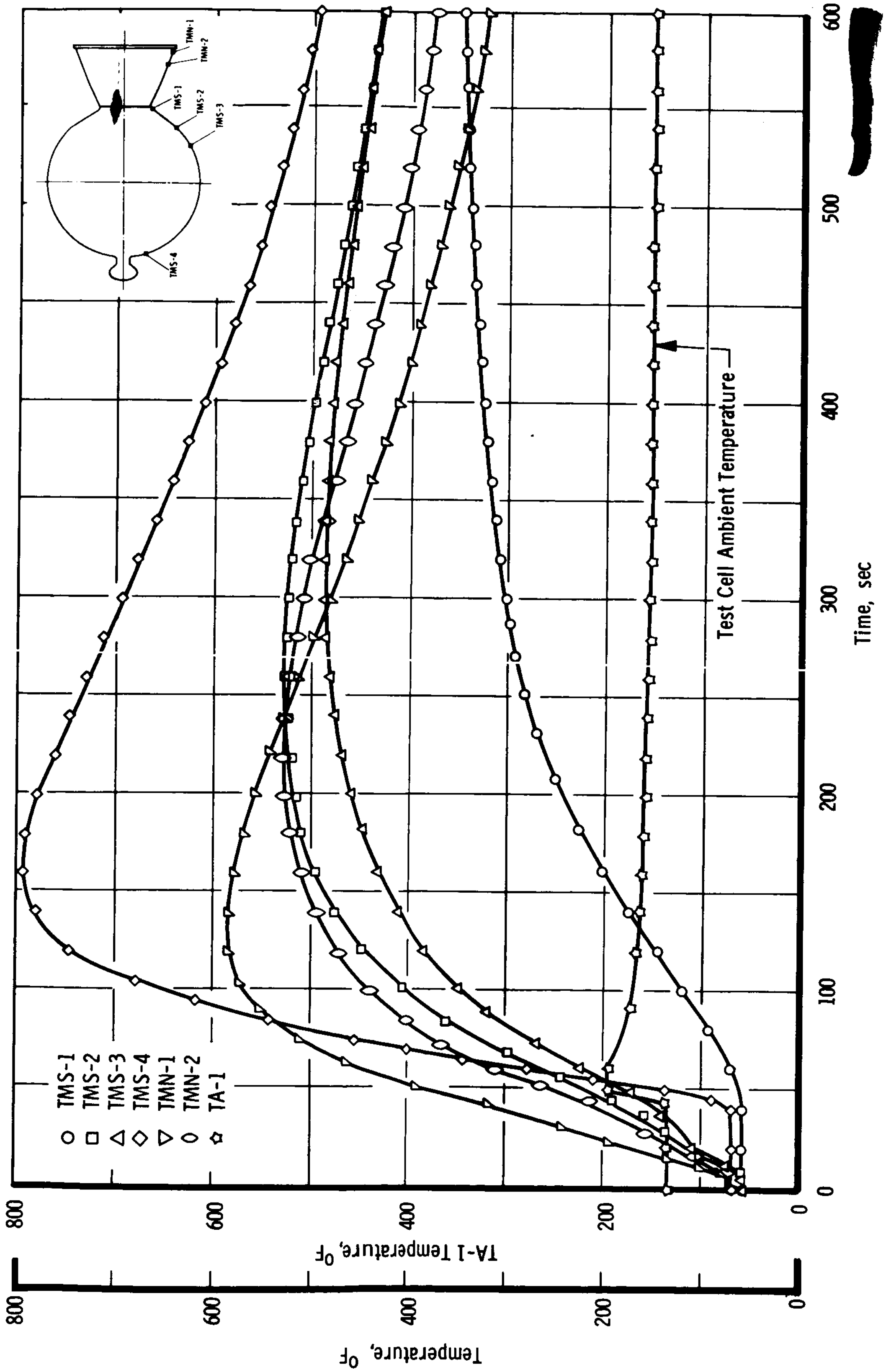


Fig. 20 Comparison of Rolling Moment

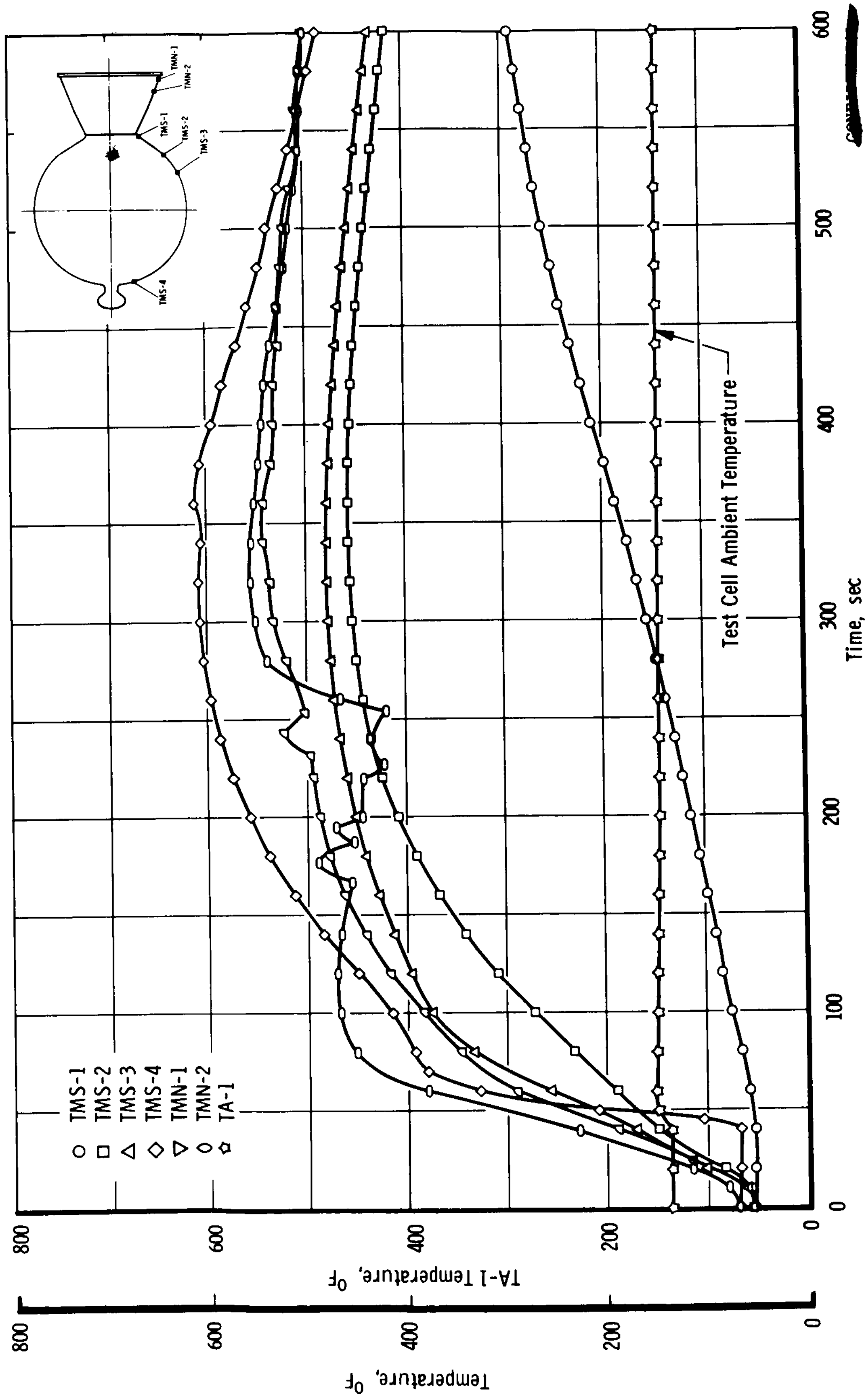
~~CONFIDENTIAL~~



a. S/N A22-2

Fig. 21 Motor Case and Nozzle Temperature Data

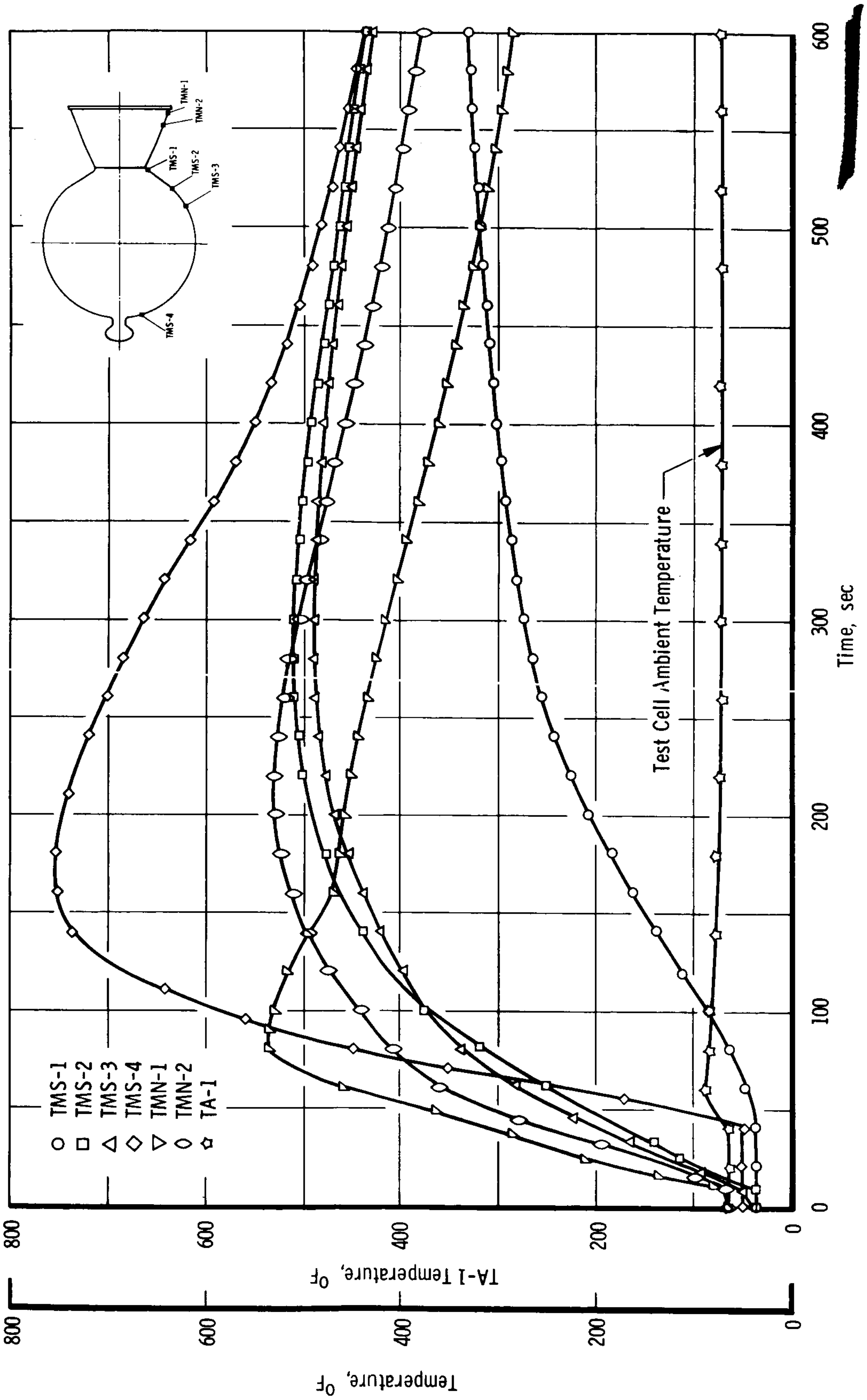
[redacted]



b. S/N A22-3

Fig. 21 Continued

[redacted]



c. S/N A22-4

Fig. 21 Concluded

TABLE I
THERMAL GRADIENT DATA

Motor S/N	A22-2	A22-3	A22-4
Zone 1 (forward jacket)	67 ± 7°F	67 ± 7°F	52 ± 7°F
Zone 2 (aft jacket)	30 ± 5°F	30 ± 5°F	15 ± 5°F
Zone 3 (case thrust skirts)	10 ± 8°F	10 ± 8°F	-5 ± 8°F

Grain Thermocouple Temperatures at Completion of Gradient Conditioning

TG-1*	42°F	40°F	31°F
TG-2*	40°F	32°F	20°F
TG-3*	57°F	55°F	43°F
Average	49.0°F	45.5°F	34.3°F

*TG-1 and TG-2 were located 180 deg apart on the aft surface of the propellant grain and were on a radius of 20.5 in. for the centerline of motor. TG-3 was in the head end of the motor and one inch from the Pyrogen well insulating.

TABLE II
MOTOR COMPARISON DATA

Motor S/N	Date Fired	Manufacturer's Stated Propellant Weight, lb	Vacuum Correction Total Impulse, lb_f-sec	Vacuum Correction Specific Impulse, lb_f-sec/lb_m	A/A*	Grain Temperature at Ignition, °F	Total Burn Time, sec	Thrust Delay Time, msec	C_F
A21-11	7/6/64	1197.80	348,750	291.2	51.24	48	46.5	125	1.834
A21-12	7/15/64	1198.76	348,950	291.1	51.08	49	46.5	127	1.859
A21-17	8/18/64	1228.96	357,880	291.2	51.02	52	46.5	126	1.858
A21-18	8/26/64	1229.55	358,290	291.4	50.95	53	48.3	134	1.809
A21-23	1/1/64	1229.01	357,300	290.7	50.97	54	46.6	122	1.840
A21-24	9/9/64	1231.82	358,580	291.1	50.90	53	47.0	119	1.874
A22-3	5/13/65	1250.61	362,000	289.3	50.71	Gradient[1]	50.0	130	1.856
A22-2	5/18/65	1299.42	375,890	289.5	50.85	Gradient[1]	50.0	125	1.864
A22-4	5/20/65	1250.59	361,470	289.0	50.97	Gradient[1]	52.0	99	1.859

[1] See Table I

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3. REPORT TITLE

ALTITUDE PERFORMANCE EVALUATION OF THE MAIN RETROGRADE THRUST ROCKET FOR THE SURVEYOR LUNAR SPACECRAFT (SUMMARY OF NINE TE-364 FIRINGS) [redacted]

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5. AUTHOR(S) *(Last name, first name, initial)*

Domal, A. F., ARO, Inc.

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N/A	National Aeronautics and Space Administration (NASA), Western Operations, Pasadena, California

13. ABSTRACT

Nine Thiokol Chemical Corporation TE-364, spherical, solid-propellant rocket motors, designed for use as the main retrograde thrust motor in the Hughes Aircraft Company Surveyor Spacecraft, were tested in Propulsion Engine Test Cell (J-5) at maximum simulated altitudes ranging from 110,000 to 116,000 ft. The objectives of testing were to: demonstrate an altitude ignition capability, measure altitude ballistic performance at a preselected grain temperature and also with a thermal gradient imposed on the motor/propellant assembly, determine the axial thrust vector excursion throughout motor operation, verify structural integrity of each motor during operation at near vacuum conditions, measure the low-range combustion chamber pressure after primary burning is complete, accomplish and document the AMR antenna separation, record dynamic forces at motor mounting plane, and measure exhaust plume radiation heat flux. (U)

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